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Clarendon Press Series

RIVERS AND CANALS

VERNON-HARCOURT

London

HENRY FROWDE

OXFORD UNIVERSITY PRESS WAREHOUSE

7 PATERNOSTER ROW

Clarendon Press Series

A TREATISE

ON

RIVERS AND CANALS

RELATING TO THE

CONTROL AND IMPROVEMENT OF RIVERS

AND

THE DESIGN, CONSTRUCTION, AND DEVELOPMENT OF CANALS

BY

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VOL. I.—TEXT

Oxford
AT THE CLARENDON PRESS
1882

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PREFACE.

In preparing a course of lectures on 'River and Canal Engineering,' which I was requested to deliver at the School of Military Engineering at Chatham in 1880, it appeared to me that a book might be useful which should present, in a simple and concise form, descriptions of the principal and most recent works on rivers and canals, at home and abroad, and the principles on which they are based.

Within the last ten years much has been accomplished in the somewhat neglected domain of inland navigation improvement. Thus the Amsterdam Ship Canal has been completed and opened; the Panama Canal has been projected and commenced; a new outlet has been provided for the River Maas, and the navigable condition of the Delta of the Mississippi has been entirely transformed. Considerable progress has been made in the same period in the improvement works on the rivers Clyde, Tyne, and Tees.

Other works also of less recent date have become sufficiently established to admit of some estimate being formed with reference to their prospects of maintenance; such as the Suez Canal, and the embankment of the estuary of the River Seine.

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Many improvements too have been introduced, quite recently, in the construction of movable weirs across navigable rivers, a branch of works which has hitherto been little attended to by English engineers.

The control also of river floods becomes every year a more pressing consideration.

Besides these subjects, elementary topics have been introduced into the book in the hope of making it useful to students.

As the value of a book of this kind depends much upon the illustrations, which both help to elucidate the subject and obviate the necessity of detailed descriptions, I have inserted several Plates. The materials for these have been obtained from the best available sources; and I must acknowledge the obligation I am under to the Council of the Institution of Civil Engineers for their kind permission, given through the Secretary Mr. James Forrest, to reproduce several illustrations which have been published in the 'Minutes of Proceedings.' I am also indebted to the valuable French treatises by MM. de Lagrené and Malézieux on inland navigation, and to the Annales des Ponts et Chaussées, for some illustrations of French works.

L. F. VERNON-HARCOURT.

6 Queen Anne's Gate, Westminster.
January, 1882.

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RIVERS AND CANALS.

CHAPTER I.

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RIVERS form a natural and easy means of communication between the sea and the interior of a country, and afford safe and convenient roadsteads for vessels. They also furnish the chief sources of water-supply; and the most fertile districts are situated along their banks. Consequently most of the important cities of the world have been built on the banks of rivers. Rivers are also the main arteries for the drainage of a country; but, whilst they are most valuable for this purpose, for irrigation, and as a source of water power, they are liable to spread ruin and devastation in their valleys when they overflow their banks. Rivers are not always suitable for navigation, in their natural condition, even in the lower portions of their course; and, owing to the continual changes they tend to produce in their channels and at their outlets, they are liable to deteriorate if left to themselves. Accordingly the maintenance, control, and improvement of rivers constitute one of the most important, and at the same time one of the most difficult branches of civil engineering.

Before entering upon the consideration of the various works which may be carried out on rivers, in order to improve them

for navigation or for other purposes, it is desirable to investigate briefly the physical peculiarities of rivers on which the nature and extent of the works that it may be advisable to execute upon them largely depend.

Variations in Rainfall. Rivers are the means by which the rainfall of a district is conveyed to the sea. It is important, therefore, in studying the characteristics of any river, to ascertain, as nearly as possible, what is the greatest and least rainfall in a given period over its drainage area, the seasons at which the maxima and minima occur, and their extent and duration.

In tropical countries rivers are frequently nearly dried up in the dry season, and immoderately swollen during the rainy season. In temperate regions river floods are generally of less magnitude and less periodic: they usually occur in the most rainy months, except in the case of rivers of glacier origin, whose floods take place in hot summer weather from the melting of the ice of the glaciers and the mountain snow. The Rhone is an instance of this latter class of river, for, being fed by the glaciers of the Alps, its greatest flow occurs in the summer and its least in December and January.

The amount of rainfall varies considerably in different parts of the world, being very great on the western coast of South America, on the east coast of Africa, and on the south-west coast of India. It attains a total depth of about 290 inches in the year at Matuba in Guadeloupe; 260 inches at Uttray Mullay on the Malabar coast, and 190 inches at Sierra Leone; whereas no rain falls over the Sahara desert, and some parts of central Asia and of America. Even in Great Britain the annual rainfall varies between about 20 and 130 inches according to the locality.

Evaporation and Percolation. The whole of the rain falling over a river basin does not find its way into the main river which drains the basin and connects it with the sea. Some of the rain is returned to the clouds by evaporation;

a portion sinks into the soil and affords moisture to trees and plants, and a portion fills subterranean cavities which form the sources of springs.

Evaporation varies with the locality, the season of the year, the state of the weather and the wind, and the nature of the soil on which the rain falls. From a series of observations, conducted by Mr. Charles Greaves for about twenty years, and recorded in his Paper on 'Evaporation and Percolation,' published in the Minutes of Proceedings of the Institution of Civil Engineers for 1876, it appears that in the valley of the Lee, where his gauges were set up, evaporation from earth is fairly uniform from year to year, seldom exceeding 25 inches or falling below 17 inches in the year; and still more uniform from a surface of water, never exceeding 27 inches or falling below 17 inches: it is greatest from a surface of water in summer, and from the ground in winter.

Percolation depends on the nature of the soil and the weather, and varies greatly, according to Mr. Greaves, from year to year. It is small in amount through earth, but large through sand; and no percolation takes place in warm summer weather. The greatest amount of percolation occurs with melting snow, and especially with small falls of snow followed by a thaw. Water penetrating into the ground to a depth of two or three feet appears to be removed from the influence of evaporation.

The most reliable experiments made in France on evaporation from a surface of water are those which were made at various stations on the Bourgogne Canal during a period of fourteen years, large basins having sides $6\frac{1}{2}$ feet in length being employed. Between 1839 and 1852 the average annual rainfall at Dijon was 26·89 inches, and the mean annual evaporation 26·10 inches: at Pouilly the rainfall was 31·53 inches, and the evaporation 22·24 inches; and at St Jean de Loisne the rainfall was 33·79 inches, and the evaporation

22·27 inches. These figures give a total average of 30·74 inches of rainfall, and 23·54 inches of evaporation, or a ratio of evaporation to rainfall of 76·57 per cent. This ratio corresponds very closely with the ratio of 77·77 per cent. which Mr. Greaves deduced from his experiments. This concordance of results is the more remarkable and satisfactory when it is considered that the two series of experiments were conducted in different countries, at different periods, and with different sized gauges.

Influence of Forests. The foregoing statements indicate that evaporation produces a very considerable diminution in the rainfall available for supplying any watercourse. Forests effect a great reduction in evaporation, and consequently increase the flow of rivers. It was found in some observations made at the forest of Halatte in 1874, that, in a period of eleven months, the rainfall over the forest was 1⅓ inches more than the rainfall in the adjacent open country. Taking the rainfall over the forest at 100, the rainfall in the open country was 92·5, and 62 under the trees; but the loss from evaporation under the trees was only one third of that on the open ground, which latter was at least 70 per cent.; so that the ratio of effective rainfall in the open country and in a forest, as gathered from these observations, is as 1 to 1·44. In reality, however, the effective rainfall in a forest is considerably higher than this ratio would indicate, owing to the prevention of evaporation from the ground in a forest by the covering of leaves. The ratio of evaporation in the open country to evaporation under trees has been put by some observers as high as 5 to 1.

It is very difficult to arrive at correct results as to the amount of rain that penetrates through trees, as it depends on the nature of their foliage, the season of the year, and the position of the rain gauges, which would give too low results if placed under the shelter of the leaves and too high results if placed under their drip.

It is doubtful to what extent the removal of forests affects the rainfall of a district; but it is certain that forests tend to equalise the flow of rivers by causing the rain to reach the watercourses more gradually. Moreover forests increase the available rainfall by reducing evaporation, especially in the summer months when water is most needed. Forests are specially valuable on impermeable strata and on mountain sides, where, by regulating the downward flow of the rain and by binding together the loose soil, they diminish the rapid rise of torrential streams, arrest the washing away of the soil, and prevent the formation of gullets which facilitate the descent of the water. Grass also has similar beneficial effects; and the removal of grass, through allowing great herds of cattle to graze too freely on the pastures, has caused serious damage on the slopes of the Alps. Laws were accordingly passed, in 1860 and 1864, to encourage the growth of trees and grass in the department of the High Alps, for the purpose of stopping the injuries resulting from the rapid descent of the rainfall down the denuded slopes; and the effects of the increase of vegetation have proved very satisfactory.

Period of Rainfall. The total amount of rain falling over the area of a river basin in any given period is not necessarily any measure of the discharge of the river.

As evaporation is very active in the summer, most of the rain which falls during the summer months is returned to the atmosphere, and only a small proportion finds its way into the rivers, unless the slope on which it falls is very steep, the strata of the basin impermeable, and the rainfall very great in a short period. Winter rains, on the contrary, find their way almost entirely into the river which drains the basin on which they fall, as they fall upon ground saturated by the wet of autumn, and when evaporation is nearly suspended. A continuous or very heavy rainfall produces a greater effect on the discharge of a river than the

same amount of rain distributed over a longer period. In many cases the greatest river floods are produced when a heavy rainfall takes place on melting snow.

Summer rains accordingly, in temperate regions, produce much less effect on the flow of rivers than rains in the winter and spring; and in many instances a drought in the early autumn may be predicted at the commencement of the summer if the rainfall has been small in the preceding winter and spring.

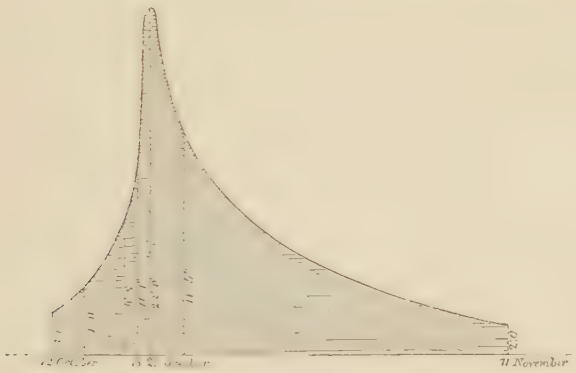
Permeable and Impermeable Strata. The nature of the strata forming the basin of a river and its tributaries exerts a very marked influence on its flow.

Where the strata are impermeable, the rain falling over the basin is rapidly discharged by numerous little rivulets into the main stream, and the river is torrential in its character. It rises very rapidly in rainy weather, and its fall is also rapid; and in continued dry weather it becomes more or less dried up. As however no strata are absolutely impermeable, some of the rain sinks into the fissures in the ground, and is delayed in its flow to the river. Accordingly, the rise of a torrential river is always more rapid than its fall, which is delayed by the later arrival of the rain that has penetrated below the surface. The accompanying sketch (Fig. 1), indicating the rise and fall of a flood of the river Loire, will serve to illustrate the characteristics, peculiar to the floods of torrential rivers, referred to above.

Where the strata are permeable, the rain sinks into the ground, and only finds its way gradually into the main stream. Consequently the rise of a river traversing permeable strata is more regular than that of a torrential river. The floods, however, of rivers flowing over permeable strata are more injurious to the adjacent lands, owing to their longer continuance, than the more rapidly rising floods of torrential streams which rapidly subside.

The annexed sketch (Fig. 2), showing the rise and fall of

a flood of the river Seine, when compared with the preceding one (Fig. 1), indicates the different nature of a river flood in a permeable basin from that in an impermeable basin, or the

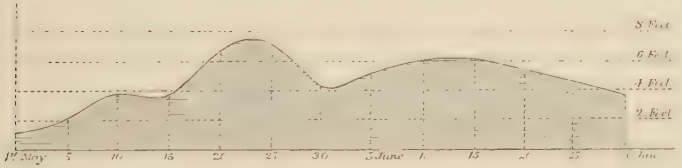


Flood of the Loire at Roanne, 1846.

Fig. 1.

difference between the floods in gently flowing rivers and in torrential rivers.

The basins of principal rivers are generally composed of strata of various degrees of permeability; and whilst some



Flood of the Seine at Bray, 1854.

Fig. 2.

of the tributaries of the principal river draining a basin flow over impermeable strata, others perhaps traverse permeable strata.

The principal river possesses, in such cases, mixed characteristics which depend on the proportion of permeable and

impermeable strata over the basin, and may vary in different parts of its course, and even at different periods, according as the rainfall predominates over one or other portion of the basin.

Available Rainfall. Attempts have been made to ascertain what proportion of the actual rainfall, over the area of a river basin, finds its way into the river. A knowledge of this proportion for different strata would be very valuable, as then, knowing the area and nature of any river basin, it would be possible to deduce the discharge for any given rainfall. This proportion is specially affected by the degree of permeability of the strata forming the basin; for whereas the rain falling on an impermeable stratum finds its way rapidly into the river, when falling on a permeable stratum it sinks into the soil, and besides affording a considerable amount of moisture to vegetation, it supplies springs which either do not flow into the river at all, or in many cases join it at lower parts of its course.

M. Baumgarten observed that the discharge of the Garonne above Marmande amounted to 65 per cent. of the rainfall; and M. Collin found that the same percentage applied to the watercourses on the clays of the lias of Auxois. For the Po M. Lombardini established a percentage of 75 for the discharge as compared with the rainfall. The Hydrometric Commission of Lyons determined the percentage in the case of the Saône, and found it 53 at Trévoux, and 50 at Lyons. M. Belgrand gives the ratio of the discharge to the rainfall for the Upper Seine as 0·236 to 1; and for the Eure at Louviers M. Sainte-Claire found that it amounted to only 0·155 to 1.

From these data M. de Lagrené deduces that the coefficient of discharge in relation to rainfall is ·75 on impermeable strata, and only ·15 on very permeable soils where the rain sometimes filters through into a different basin from the one on which it fell.

Basins of Rivers. The basin of a river is the whole area which is drained by the river. It is bounded by the summits of the valleys of the river and its tributaries. The divisional line between two adjacent basins is commonly called the watershed, derived no doubt from the German equivalent word *Wasserscheide*, signifying water-separation. As, however, the term watershed is rather ambiguous, and is sometimes used to denote the slope of a river valley, or even the whole basin of a river, it seems desirable to substitute the term water-parting for the line of separation from which the water flows in opposite directions.

River basins vary greatly in extent; and the size of a river is necessarily somewhat proportionate to the area which it drains, whilst its actual discharge, per unit of area, is influenced by the various physical conditions already considered.

The largest river basin in England is that of the Thames, which has an area of 5,162 square miles: next in size comes that of the Severn, with an area of 4,437 square miles; and then the Yorkshire Ouse basin, having an area of 4,207 square miles; whilst the Medway, which has the appearance of a large river at Chatham, has a drainage area of only 997 square miles. The chief river of Europe, the Danube, has a length of 1,700 miles, and its basin is 300,000 square miles in extent. In India the largest river basin, that of the Ganges, has an area of 391,000 square miles; whilst the Dhadur basin has an area of only 1,800 square miles.

It is, however, on the American continent that the longest rivers and largest river basins are found. The Mississippi, for instance, in North America, the greatest river in the world, is 4,500 miles in length, and has a basin extending over 1,244,000 square miles, more than four times the size of the Danube basin, and nearly equal to the basins of the four largest Indian rivers, the Ganges, the Indus, the Bramaputra, and the Irrawaddi, put together, which have a total area of 1,275,800 square miles.

Influence of Lakes. Lakes exercise a regulating influence on the flow of rivers issuing out of them, as they serve as large natural storage reservoirs of rainfall. For a river in flood flowing into a lake produces only a very slight rise over the whole area of the lake, and is prevented from rapidly swelling the discharge of the river below, which has accordingly a more uniform flow than it had above the lake. Thus for instance the Rhone and the Rhine are more regular in their flow on issuing from the lakes of Geneva and Constance than in the upper portions of their course; and the river St. Lawrence, being fed almost entirely by the lakes Superior, Huron, Michigan, Erie, and Ontario, is so uniform in its flow that its level remains nearly always constant.

Fall of Rivers. As a river forms its own bed in the bottom of the valley through which it flows, the nature of the bed depends on the geological strata which lie on the surface of the valley, or which the river has laid bare in the course of ages. The general form of the bottom of a river valley varies according as the strata are permeable or impermeable. The water flowing down the slopes of valleys composed of impermeable strata gradually wears away the projections and fills up the hollows with soil from above, so that the slopes become curved as indicated in the sketch (Fig. 3). The rain,

Section of the valley of a river on impermeable strata.

Fig. 3.

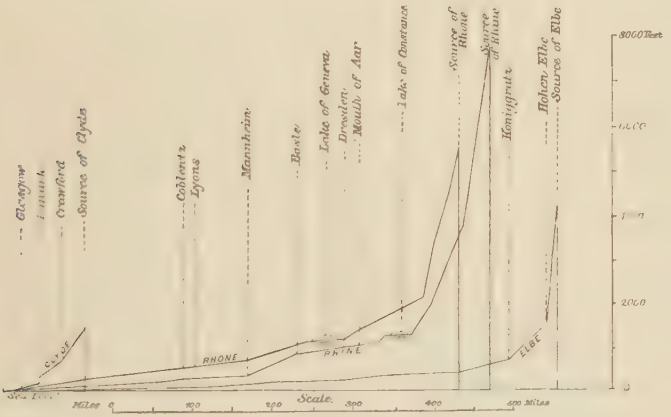
however, falling on a permeable river basin, as it sinks into the soil, does not materially modify the form of the slopes. Accordingly the valley, in this case, generally retains its original form, being nearly level at the base, or sometimes slightly raised along the banks of the river in consequence

of the successive deposits produced by the river in flood time, as shown on the accompanying sketch (Fig. 4).

Section of the valley of a river on permeable strata.

Fig. 4.

The fall of the bed of a river corresponds approximately to the general fall of the land over which it flows, and varies considerably in different localities. Usually the fall is greatest near the source of the river, gradually diminishing as it approaches the sea (see Fig. 5). Rivers rise at the



Fall of Rivers.

Fig. 5.

summits of their valleys, and if a river valley is terminated by a high mountain range the river commences as a torrent, with a more or less rapid fall according to the declivity of the mountain side. If the mountains are near the sea into which the river flows the average fall of the river is considerable, as on the western coast of America. When, on the contrary, the mountain ranges are separated from the ocean

by large extents of plains, as on the eastern side of America, the fall of the river bed is gentle.

Transportation of Material. Rivers, besides conveying rainfall to the sea, are also the transporters of alluvium. Gradually, though slowly, all rivers are bringing detritus down their valleys, and the materials of the mountains are being carried to the sea. Glaciers, in their slow but irresistible descent, grind the rocks of the mountain slopes down which they imperceptibly glide, and when melting in the valleys carry a large quantity of matter along with them. The velocity of the flow of rivers in the earlier portion of their course enables them to hold this matter in suspension; but as the fall of their bed and consequently their velocity decreases the heavier particles fall to the bottom, and tend to fill up the river bed. This deposit is generally scoured out in flood time, and either carried lower down the river or strewn over the valley. A river flowing through a lake deposits all its sediment in the lake, as its velocity is checked on entering the lake. For instance, the turbid Rhone on entering the lake of Geneva deposits all the material which it has brought down from the Alps, and issues at Geneva as pure and clear as the waters of the lake, but is soon after changed into its original turbid condition by mingling its waters with its glacial tributary the Arve.

River beds are accordingly liable to constant alteration, and any works which tend to alter the rate of flow of rivers are liable to modify the position and amount of deposit of the sedimentary matter with which they are charged.

Various experiments have been made to establish a relation between the rate of flow and the size of the particles moved by a current. Thus, according to Dubuat, a current of water flowing at the rate of 3 inches per second would move potter's clay; at the rate of $7\frac{1}{2}$ inches would move gravel of the size of a pea; at the rate of 1 foot would move gravel of the size of a small bean, and at the rate of 2 feet 1 inch

per second would be capable of moving round pebbles an inch in diameter. When the velocity of a current diminishes the heaviest particles are deposited first.

Divergence of Current. The instability of a river channel is not confined to the bottom of its bed. A river rarely flows, especially across a level plain, in a straight and uniform channel. A very slight impediment, such as a fallen tree or harder ground at one bank, will direct the main current against the opposite bank, which, if composed of soft materials, is gradually washed away, and deposit collects near the other bank, so that the course of the river is by degrees modified. After impinging against one bank the current is again deflected back to the other bank, thus gradually producing and intensifying the serpentine course so noticeable in many rivers when flowing through plains (Fig. 6). The greatest current is produced close to the concave bank, which, besides promoting the washing away of the bank, produces

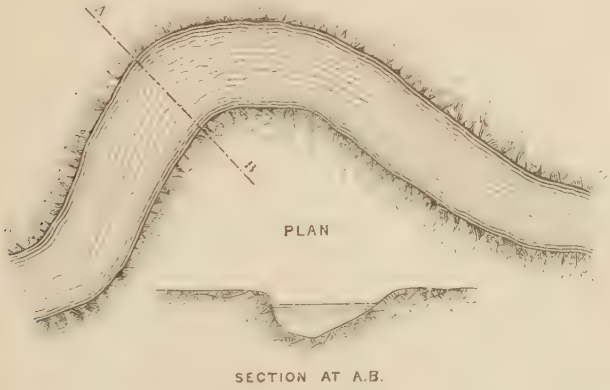


Fig. 6.

also a scour at the bottom. Accordingly in winding rivers the channel is deepest close to the concave bank, and gradually shoals towards the convex bank, as shown in the section; whereas at the succeeding bend the deepest part of

the channel has shifted with the current and is close to the opposite bank.

The branch of the subject treated of in this chapter is intimately connected with meteorology and geology, but, nevertheless, it forms the groundwork upon which schemes of river improvement must be based. The amount of water available at the driest periods; the means by which its increase may be promoted, or its loss by evaporation diminished; the changes which are occurring in river channels, their causes, and their rate of progress, are important elements in considering the navigable capabilities of a river. The regulation of the discharge of a river, so that its flow may not be too rapid for navigation, or too slow and cause floods, can be properly entered upon only after a careful study of the physical features of the valley of the river. Accordingly the greater the number of meteorological and geological data that can be collected, the more likely are the works undertaken to produce satisfactory results.

CHAPTER II.

MEASUREMENT OF DISCHARGE.

Definition of Terms:—Discharge; Slope; Sectional Area; Wetted Perimeter; Hydraulic Mean Depth; Mean Velocity. Measurement of Cross Sections. Velocity Observations:—Floats; Current-Meters; Gauge-Tubes; Hydrodynamometer. Remarks on the Methods of Measuring Velocities. General Formulæ of Discharge; Position of Maximum Velocity; D'Aubuisson's and Downing's Formula; Various other Formulæ; Kutter's Formula.

Definition of terms. The *discharge* of a river is the amount of water which it passes into or towards the sea in a given unit of time. It is usually reckoned in cubic feet per minute or second.

The *slope* or *fall* of a river is the inclination of its water surface, and it may be conveniently expressed in feet and inches per mile.

The *sectional area* of a river is the area of the cross section of its channel taken at right angles to the current, and is expressed in square feet. When the actual or possible discharge of a river is to be measured, only that portion of the cross section is taken into account which is below the actual or assumed water line.

The *wetted perimeter* is the portion of the boundary line of the cross section of the channel below the water line.

The *hydraulic mean depth*, or as it is sometimes termed the *hydraulic radius*, is obtained by dividing the sectional area of the stream by the wetted perimeter of the channel. For instance, if a channel (Fig. 7) has a base of 20 feet, with slopes on each side of $1\frac{1}{2}$ to 1, a depth of water of 6 feet, and consequently a width at the surface of 38 feet; the sectional

area of the stream is 29 feet × 6 feet = 174 square feet, and its hydraulic mean depth

$$= \frac{\text{sectional area}}{\text{wetted perimeter}} = \frac{174}{41{\cdot}6} = 4{\cdot}18 \text{ feet.}$$

The *mean velocity* is the average velocity of all the elements of the current.

The amount of the discharge is obtained by multiplying the sectional area of the stream by the mean velocity.

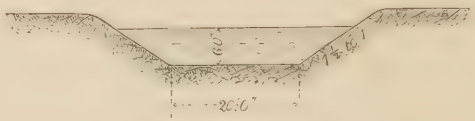


Fig. 7.

Measurement of Cross Sections. In order to ascertain the discharge of a river it is necessary, in the first place, to obtain its sectional area. It is advisable in gauging a river to select as straight and uniform a reach as possible, and where the flow appears to be regular, as this indicates that the section is fairly uniform. To ensure accuracy several cross sections should be taken along the part of the river selected. The cross sections are taken by making soundings, at known intervals, in a straight line across the stream.

When the river is not very broad, a strong thin rope, previously wetted and pulled out, tightly stretched at right angles to the stream, in the line of the proposed cross section, from bank to bank, serves conveniently as the base line for the soundings. Where great accuracy is required a wire should be employed in place of a rope. The positions of the soundings are measured along the rope, starting from the edge of the water on the right bank. When the depth does not exceed about 15 feet the soundings are most conveniently taken by means of a round, slightly tapering, wooden pole, on which the lengths are marked from the bottom upwards.

The pole must be terminated at the bottom by a broad flat piece, so that it may not sink into mud, and if the stream is strong a little lead may be inserted at the bottom of the pole with advantage. The soundings are taken from a boat kept with its head up-stream and just under the rope, so that the man taking the soundings may be able to lower the pole in the line of the rope. When the river is too deep, or the current too strong, for using a pole for the soundings, a measuring chain with a weight at the end is employed.

It is advisable, if possible, to select a time for taking the cross sections when the river is neither in flood nor very low. In flood time there is frequently considerable difficulty in fixing the cord, in keeping the boat in position, and in taking the soundings. When the river is very low there is less width of channel available for sounding, which is the easiest and quickest way of taking the measurements in the bed of the river, and there is liable to be too little water for floating the boat over the shallows.

The level of the water at the various places chosen for the cross sections, and any alterations in level whilst the soundings are being made, are obtained, either by means of a spirit-level, or by reading off the height of the water on marked gauge boards set in the water to a known datum. The measurements for the cross sections are extended from the edge of the water over the banks on each side, for a certain distance, by the ordinary process of levelling, so that the cross sections may be known for varying heights of the river.

When a river is too broad for stretching a rope or wire across it, the following method is adopted for taking the soundings and ascertaining their positions in the line of the cross section. The line of the section is marked by erecting a pole on each bank, and a man is stationed at one of the poles: then directly the boat conveying the sounding party, slowly dropping down stream, crosses the line, a signal is

made by the man on the bank, and the sounding is immediately taken, everything having been got in readiness beforehand, with the sounding chain lowered nearly to the bottom. At the same instant the exact distance of the sounding from the banks is noted, either by two observers, stationed with theodolites at the extremities of a measured base line on one of the banks, who take the angles between the boat and the base line, or by a person with a sextant in the boat taking the angles subtended by known objects on shore. Any required number of soundings can be taken in this manner, along a particular line across the river, at different distances from the banks, from which the cross section can be plotted.

Velocity Observations. Having obtained a sufficient number of cross sections, and deduced from them the mean sectional area of the river or channel under examination, it is necessary to ascertain the mean velocity of the current in order to estimate the discharge of the river. There are three general methods by which this velocity may be obtained:

1. *Floats.*
2. *Current-Meters.*
3. *Gauge-Tubes.*

1. *Floats.* The simple expedient of throwing a floating substance into a stream, and observing the time it takes to traverse a measured distance, for ascertaining the velocity of the current, presents many difficulties in practical application. A floating body indicates merely the velocity of the portion of the current in which it happens to be situated; and it is now well established that the velocity of a stream, flowing in an open channel, varies, not only at different points on the surface, but also at different depths in the same vertical line.

For surface velocities an orange forms an excellent float, as its specific gravity is very little less than that of water and it therefore floats almost wholly immersed; but pieces

of wood, cork, or other easily procurable floating substances are often employed.

All surface floats, however, are useless in windy weather, as wind has a great effect on the top layers of water, so as even sometimes to make the surface move in a direction opposite to the current below.

As it is not always possible to limit float observations to only perfectly calm days, and as surface velocities, even when correctly measured, do not indicate the mean velocity of a current, it has been found necessary to adopt other types of floats.

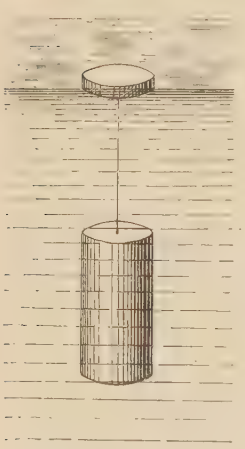
Tin tubes loaded at one end with lead, so as to sink nearly to the bottom, have been employed, in the measuring flumes at Lowell, Massachusetts, for determining the amount of water drawn from the canals. The flumes are constructed in parts of the canals, which are tolerably straight and uniform and rectangular in section, by lining the bottom and sides of the canal with smooth planking so that the current through them may be as regular as possible; and the tin tubes indicate the mean velocity of the vertical section of the stream in which they float. By means of a series of experiments with these tube floats, in which they are placed at different distances from the banks, it is possible to ascertain the mean velocity across the whole cross section of the stream with considerable accuracy.

Somewhat similar tube floats have been used by Capt. Allan Cunningham, R.E., at Roorkee, which he terms velocity rods. The rod consists of a tube, 1 inch in diameter, made of sheet tin, the lower end being formed round a short length of round bar iron such that its weight almost sinks the tube to the required depth, the final adjustment being performed, by means of some small shot, when the tube is floating in still water, so that about two or three inches may project out of water, the top being then closed by a disk of tin.

As these tube floats present an equal surface to the current

at every depth in a vertical line, the motion imparted to the tube may be considered to represent the mean velocity of the current in the vertical plane in which the float travels.

The double float is another type of float which is employed for measuring sub-surface velocities, at any point in a stream, so as to ascertain, by a series of experiments, the mean velocity of the current. It consists of a small surface float connected, by a cord, to a large float carefully weighted so as to sink in the water and keep the connecting cord stretched, but not enough to pull the surface float under water (Fig. 8). The length of the connecting cord is varied according to the depth at which the velocity is to be measured; and whilst the current imparts its motion to the lower float, this motion is rendered apparent by the corresponding movement of the upper float.



Double Float.

Fig. 8.

The extensive series of experiments on the flow of the Mississippi, made by Messrs. Humphrey and Abbot, were conducted by means of double floats. The lower floats were kegs without top or bottom and ballasted with lead so as to sink and assume an upright position. They were retained at the desired depth by surface floats, to which they were attached by cords of suitable length. The kegs, used for depths not exceeding five feet below the surface, were 9 inches high and 6 inches in diameter, with connecting cords of $\frac{1}{10}$ inch; and for depths beyond five feet, kegs 12 inches high and 8 inches in diameter were employed, with cords of nearly $\frac{1}{5}$ inch. The surface floats were made of light pine or of tin; the former were $5\frac{1}{2}$ inches square and $\frac{1}{2}$ inch thick,

and the latter ellipsoids with axes $5\frac{1}{2}$ and $1\frac{1}{2}$ inches long respectively.

The double float employed by Mr. Gordon, in a series of experiments on the flow of the Irrawaddi, consisted of two wooden cylinders 6 inches in diameter; the lower float was made one foot long and weighted with lead so that the upper or surface float, one inch thick, to which the lower float was attached by a thin cord, floated about three-fourths immersed. Mr. Gordon considers that he improved upon the Mississippi floats by using a thinner connecting cord.

Captain Cunningham employed a very similar double float, for the measurement of sub-surface velocities, which consisted of a sphere of heavy wood, 3 inches in diameter, attached by a wire to a surface float of deal, 3 inches in diameter and $\frac{3}{8}$ inch thick.

2. *Current-Meters.* Several current-meters have been designed for ascertaining the rate of flow of a current. Though differing somewhat in construction, they are all based on the same principle, that of measuring the velocity of a current by the number of revolutions it produces, in a given time, on a screw or on vanes fixed on a horizontal axis in the front part of the instrument. Two different types of current-meters are shown in Figs. 9 and 10 (p. 22). The revolutions are recorded by a system of toothed wheels, connected with the axis of the screw, which turn an indicator revolving round a graduated dial. The distance between each mark on the dial is made to correspond with the space travelled by the indicator when the current has run a certain distance, usually taken at one foot. One or more wings at the tail of the instrument keep it, when immersed, with the axis of the screw in a line with the current. A brake is fitted to the instrument, so that the screw can be set free to revolve or can be stopped, at any time, by merely pulling tight or slackening a string, above water, connected with the brake.

When the velocity of a current is to be measured, after noting the reading of the index, the current-meter is im-

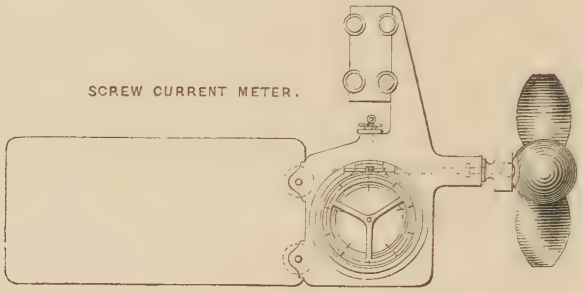


Fig. 9.

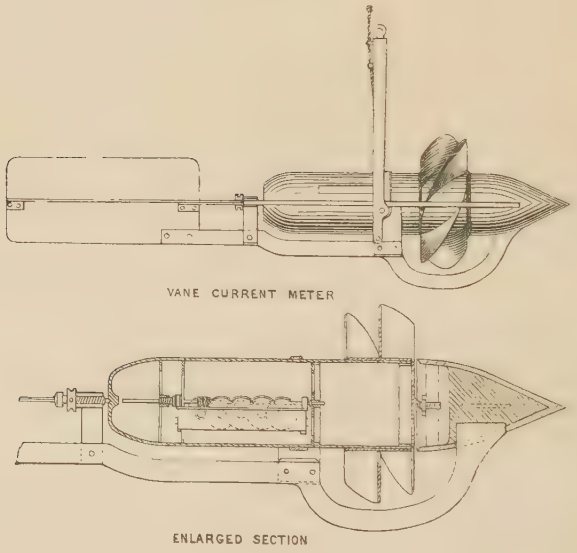


Fig. 10.

mersed at the desired position in the river, and lowered to the required depth from a boat, being held in position by one or more strings or rods. The brake is then raised, and

the time noted. As soon as the time settled for the duration of the observation has elapsed the brake is applied, the meter is lifted out of the water, and the distance traversed by the index is ascertained. If the index registers in feet, the number of divisions traversed by the index, in the given time, divided by the time, gives at once the velocity of the current in feet per minute or second as the case may be. If the mean velocity in a definite vertical plane is required, it is only necessary to lower the current-meter gradually, at a given spot, to the bottom, and then raise it again at a uniform rate. The recorded distance divided by the time will give the mean velocity of the current at the different depths of the vertical plane selected.

Theoretically, a current-meter affords an accurate measurement of the velocity of a current. Friction, however, affects the results, and has a greater influence on low than on high velocities; in fact for very low velocities most current-meters are useless, as they cease to revolve.

Messrs. Humphrey and Abbot found that the Mississippi was too deep, and its current too turbulent and irregular, to admit of the employment of a current-meter for determining its rate of flow.

Moreover, though the manufacturers profess to make the index register the exact distance run by the current, this is only approximately realised; and, for absolute accuracy, the current-meter can only be regarded as an instrument making a certain number of revolutions for a certain distance traversed by a current, varying somewhat according to the velocity, and the index considered as merely registering these revolutions. Accordingly, when very exact results are required, the current-meter should be tested, either by placing it in a stream with a uniform and ascertained rate of flow, or by drawing it along at a known velocity in still water, in order to ascertain what each division of the index, or a definite number of revolutions of the screw, actually

represent, and what allowance should be made for frictional resistance at different velocities.

In order to reduce the complication of toothed wheels which check the rotation, to detect any temporary stoppage of the rotation, and to avoid the necessity of lifting the current-meter out of water after each observation, an instrument has been designed by which the rotations are recorded, above water, by means of an electrical connection which rings a bell when a certain number of revolutions have taken place.

The same result has been attained by making the axis of the screw move a small hammer once in each or a definite number of revolutions. The hammer strikes a tightly stretched wire which passes up out of the water to a resonance box, so that each stroke of the hammer is distinctly audible.

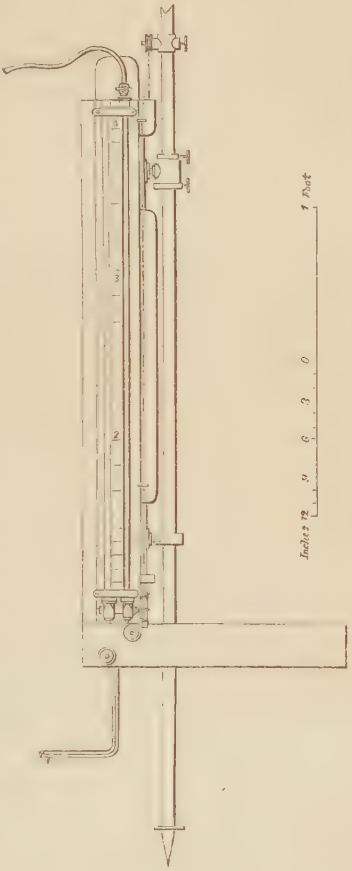
3. *Gauge-Tubes.* The original gauge-tube, as designed by Pitot, consisted of a glass tube with a short bend at one extremity at right angles to the rest of the tube, and open at both ends. The tube being immersed in a current with its straight portion vertical, and the bent part horizontal with its end facing the current, the water in the tube is raised by the pressure of the current, and the height of the column of water above the surface furnishes a measure of the velocity of the current, which is represented by the formula,

$$V = \mu \sqrt{2gh},$$

where h is the height of the column, and μ is a coefficient which can be determined by drawing the tube through still water at known rates.

M. Darcy improved upon this simple apparatus, in which the height of the column was difficult to determine, owing to the ripples on the surface of the stream and the oscillations inside the tube, and was, moreover, not quite an exact measure of the velocity. He employed two tubes (Fig. 11), $\frac{3}{8}$ inch in diameter, connected at the top by a copper tube

in which a stopcock is fastened, which enables communication to be made at pleasure with the outer air. Copper tubes are fastened at the bottom of each of the glass tubes, and bent at right angles to the glass tubes, and to each other, for a length of 3 inches, and terminated by mouthpieces having orifices of only $\frac{1}{17}$ inch diameter. The lower copper tubes have a double-acting stopcock which opens or closes them simultaneously. The upper stopcock is closed before the instrument is placed in the water; and as soon as the tubes have been immersed to the desired depth, with one mouthpiece pointing to the current and the other at right angles to it, the lower stopcock is opened, and the water rises in the tube pointing to the current; the stopcock is then closed, the instrument is raised, and the difference in level of the water in the two tubes is measured at leisure.



Gauge-Tube.

Fig. 11.

It is important to see that the mouthpieces are clear, that the tubes are kept perfectly vertical, and to wait for taking the observation till the oscillations of the column of water have ceased. It is also advisable to repeat the operation three or four times, and take the mean of the results.

This last method of measuring velocities was adopted by

MM. Darcy and Bazin in their experiments, conducted in the canals of Chazilly and Grosbois, for obtaining accurate measurements of the discharge of channels, with the view of ascertaining the laws regulating the flow of water in open channels and deriving a general formula.

Hydrodynamometer. Another form of instrument for gauging the flow of streams has been designed and used by M. de Perrodil. It measures the velocity of a current by means of the torsion produced on a wire by the pressure of the water against a disk. The disk is fixed at the end of a horizontal arm projecting from the extremity of a brass wire placed vertically in the stream. The velocity of the current is obtained by the equation $V = c\sqrt{a}$, where a is the angle of torsion, and the value of c can be determined, either approximately from the coefficient of torsion of the metal employed, or actually by experiment. The instrument used by M. de Perrodil indicated a velocity as low as $\frac{3}{4}$ inch per second; and it could be constructed so as to be still more sensitive, being in this respect superior to both the gauge-tube and current-meter.

Remarks on the foregoing Methods for Measuring Velocities. Whilst double floats were exclusively relied upon in the Mississippi experiments, and also subsequently by Mr. Gordon in his experiments on the Irrawaddi, they have been strongly condemned by Mr. Révy, and M. Bazin has recorded his opinion against them. The objections urged against their employment are, that the motion of the lower float is not accurately indicated by that of the float at the surface, and that, moreover, the upper float and connecting cord, being acted upon by a different portion of the current, modify the motion of the lower float: also that it is impossible to ascertain whether the lower float is really stationed at the desired depth, or whether it may not be lifted by eddies into a higher part of the current and be constantly shifting its position.

Mr. Révy relied entirely on screw current-meters, of the type shown in Fig. 9, for gauging the discharge of the Paranà and La Plata rivers. Probably a carefully constructed and accurately tested current-meter, in good working order, is the best instrument, in general, for measuring the velocity of currents; but the method of double floats is more serviceable and accurate than might be imagined from the very unfavourable opinions of it expressed by some writers. Mr. Gordon, in his experiments on the large river Irrawaddi, observed that the motion of the top float was too uniform to allow of the existence of the erratic movements of the lower float attributed to it by the opponents of the method; and observations made of the motion of the lower float in small clear streams lead to a similar conclusion. The tube float, moreover, is free from these objections, and no divergence from the perpendicular can occur without being manifested by the inclination of the portion of tube above the water.

The float method is valuable for measuring the rate of flow of sluggish streams in which the ordinary current-meter would not act; and, with the exception of the hydrodynamometer, which has not been hitherto extensively tried, it is the only available method in such cases.

Darcy's gauge-tube gives good results in small channels, and when the stream has a fair velocity; but it would be inapplicable to large rivers, and very low rates of flow.

General Formulæ of Discharge. All processes of gauging take time, and require a great deal of care. Naturally therefore attempts have been made to arrive at some general formula which, with a few simple data and observations, would enable an accurate calculation of the discharge of any river to be rapidly accomplished. Moreover, when a channel has to be enlarged, or a new cut made, or canals for supplying water for irrigation or other purposes constructed, it is essential to know what the maximum possible discharge would amount to; and in such cases formulæ must be resorted

to for ascertaining the possible discharge, in order that the section and fall of the channel may be designed so as to prove neither inadequate nor too large for the object to be attained.

All the formulæ proposed are to a certain extent empirical; they have either been deduced from a number of experimental data, or probable laws have been assumed and then applied to known discharges, till, by successive modifications and the introduction of coefficients, a formula which satisfies a certain number of cases has been obtained.

Mean Velocity deduced from Surface Velocity. It would be very convenient, for the purpose of simplifying and shortening gauging operations, if merely the maximum surface velocity had to be measured, and the mean velocity could be deduced from it.

Messrs. Baldwin and Whistler made experiments on the flow of water in flumes, or channels lined with planks, in order to arrive, practically, at the relation between surface and mean velocities. They gauged the actual discharge with gauge wheels, and observed the surface velocities. With a rectangular channel 27 feet 2½ inches wide, a depth of water of from 7 feet 6 inches to 8 feet 2 inches, and surface velocities of from 3·07 to 3·34 feet per second, a mean coefficient of ·857 was obtained which, multiplied into the surface velocity, would give the mean velocity. With a channel 29 feet 11 inches wide, a depth of water of from 7 feet 8 inches to 8 feet 1 inch, and surface velocities varying between 1·91 feet and 2·77 feet per second, the mean coefficient was ·814; and five other experiments gave an average coefficient of ·829. These results coincide approximately with the coefficient ·816 obtained by De Prony from experiments on the flow of water in wooden troughs, with depths of water ranging between 2 and 10 inches, and velocities from 5 to 4¼ feet per second. Messrs. Baldwin and Whistler and M. de Prony both arrived at the conclusion that the coefficients they had

obtained would require reduction for lower velocities, and need increase for higher velocities.

These experiments indicate that for water flowing in rectangular planked channels, within certain proportions of width and depth, and with a rate of flow within certain limits, the ratio between the mean and surface velocities lies between ·8 and ·85 to 1.

MM. Darcy and Bazin give the following equations for determining the mean velocity from the maximum velocity:

$$\frac{V}{U} = 1 + \frac{25{\cdot}34}{c \times 100} \text{ and } V - U = 25{\cdot}34\sqrt{RS},$$

where V is the maximum velocity, U the mean velocity, R the hydraulic radius in feet, S the sectional area in square feet, and

$$c = {\cdot}01\left\{\frac{V}{\sqrt{RS}} - 25{\cdot}34\right\}.$$

Position of Maximum Velocity. Previous to the experiments on the Mississippi, the position of the maximum velocity of flow was supposed to be always at the surface. The results, however, of these experiments indicate that, after making due allowance for the resistance of the air as well as for the effects produced by wind, the position of maximum velocity is frequently below the surface of a river, and this has been confirmed by other observers. The general view held now as to velocities of flow, in any vertical plane parallel to the current, is that these velocities vary as the abscissæ of a parabola whose axis is parallel to the water surface and may be below it. Messrs. Humphreys and Abbot found that, in horizontal planes, the velocity increased gradually and uniformly with the distance from the banks till the thread of the current was reached.

From a survey of the results obtained in the Mississippi experiments, the velocity appears to differ very little at different depths; it at first increases, and soon begins to decrease as the depth below the surface increases. The point

of maximum velocity is found at very variable depths below the surface; and the degree of curvature of the parabola varies with the stage of the river. When the river is high the maximum velocity attains its greatest depth; and the curve of velocities is flatter when the river is at its greatest height. When the river is low the position of maximum velocity is near the surface. The equation for the parabola corresponding to the grand mean curve of the Mississippi observations is

$$V = -0{\cdot}79222d^2 + 3{\cdot}2611,$$

where V is the velocity in feet, and d is the distance from the axis in fractional parts of the whole depth considered as a unit.

D'Aubuisson's and Downing's Formula. It is easy to understand the impossibility of obtaining a simple formula applicable to all cases. The simplest type of formula for calculating the discharge of any channel is that of D'Aubuisson, which, converted by Downing into English measures, is

$$V = 100\sqrt{RS},$$

where V is the velocity in feet per second, which, multiplied by the average cross section A, gives the discharge $D = VA$, and R is the hydraulic radius in feet, and S the actual slope of the water line, or the proportion of its fall to the length.

Various Formulæ of Discharge. The formulæ of Young, Neville, Eytelwein and others, are in reality merely modifications of Downing's formula occasioned by the employment of different coefficients. The following table, taken from Jackson's 'Hydraulic Manual,' a valuable treatise on this subject, furnishes the various coefficients adopted. Putting the formula into the form $V = c \times 100\sqrt{RS}$, the various values given to c are as follows:—

	Value of c.
D'Aubuisson, Downing, and Taylor	1·
Young, for large streams	·843
Neville, for rivers with velocities less than 1·5 feet per second ...	·923
„ „ „ exceeding 1·5 feet per second ...	·933
Eytelwein	·934
Beardmore	·942
Stevenson, for rivers discharging 30 cubic feet per second ...	·690
„ „ „ 2500 „ „	·960
Leslie, small streams...	·680
„ large streams	1·

These coefficients, however, are by no means generally applicable. For instance, Downing's coefficient is only correct for a discharge of about 17,000 cubic feet per second, it gives too low results for larger discharges and too high results for smaller discharges; whereas Eytelwein's coefficient, which approximates to several others, is only suitable for a discharge of about 2,000 cubic feet per second, and is too low for larger and too high for smaller discharges.

The formula obtained by Messrs. Humphreys and Abbot is not applicable to small rivers; whilst the formula of MM. Darcy and Bazin is not suitable for large rivers.

Kutter's Formula. It is evident that no general formula of discharge can be correct in which the coefficient does not vary with the size and condition of the channel. Herr Kutter, realising this principle, has arrived at the following formula, expressed in English measures:—

$$Q = \left(\frac{\frac{1{\cdot}811}{N} + 41{\cdot}6 + \frac{0{\cdot}00281}{S}}{1 + \left(41{\cdot}6 + \frac{0{\cdot}00281}{S}\right)\frac{N}{\sqrt{R}}} \right) A\sqrt{RS},$$

where Q is the quantity of water in cubic feet discharged per second, A is the sectional area of the channel in square feet, R the hydraulic radius in feet, S the slope, or the fall divided by the length, and N the coefficient of roughness, to which Herr Kutter gives values varying between ·020 and ·035, according to the nature of the bed and the condition of the

channel. Mr. Jackson considers that this formula is applicable to all cases; but its complicated appearance, which cannot be avoided if it has to suit large and small discharges alike, is liable to prevent its rapidly supplanting the simpler, though comparatively inaccurate formulæ which have preceded it.

Whilst the various instruments for measuring the discharge of a river afford means of ascertaining, with tolerable accuracy, the amount of water that actually passes down any part of a river at any given period, the formulæ give the amount of water any new or enlarged channel, of known dimensions and fall, should discharge. The gaugings accordingly indicate the available discharge; and the formulæ enable an estimate to be formed as to the depth and velocity this stream of water would have in an enlarged or modified channel. The gauging processes are also valuable for checking the accuracy of the formulæ for various discharges. Both gaugings and formulæ are required for the purposes of river improvements; whilst the formulæ are essential for the design of new river cuts, or of drainage and irrigation canals.

CHAPTER III.

RIVERS AND CANALS.

Rivers—Variable Flow. Observations of Rise and Fall. Highest and Lowest Water-Levels. Minimum Depth of Channel. Primitive Method of River Navigation. Stanches. Alteration of Channel. Cross Jetties. Longitudinal Jetties. Dredging Hard Shoals. Easing Bends and Making Straight Cuts. Introduction of Locks and Level Reaches. *Canals*—Works for Canals. Supply of Water. Consumption of Water. Introduction of Supply. Uses of Canals. Canals for Drainage, Irrigation, and Water-Supply.

RIVERS.

Variable Flow of Rivers. As the discharge of a river is the product of the sectional area into the velocity, and the velocity varies with the slope and the hydraulic mean depth, it follows that in proportion as the fall of a river is greater its sectional area is less for the same discharge. Consequently the depth of a torrent is small compared to that of a gently flowing river; and the occurrence of an increased rate of flow in any part of a river indicates a diminution in the sectional area.

Torrents are unsuitable for the purposes of navigation, both on account of the velocity of their flow and their want of depth. They may, however, be employed as water power for turning turbines or water wheels; but, in many cases, the want of regularity in their flow and their liability to dry up prevent their being of use, except where a temporary employment of power is sufficient. A river to be perfect for navigation should be tolerably straight, without sharp bends, with a fairly uniform breadth and depth, and consequent regular flow, without a scarcity of water in dry weather, or

too full and rapid a flow in flood time. Such a type of river is seldom found. Most rivers, in their natural state, present constantly varying conditions of breadth and depth, alterations in fall and flow, and a more or less winding course. When deposit occurs in the channel, owing to loss of velocity, the river becomes shallow, and, being unable to scour out its bed, it widens out in order to maintain its discharge; but when the fall suddenly increases, and the bed is rocky, rapids occur. With the exception of some of the largest rivers of the world, few rivers indeed are by nature perfectly convenient for navigation beyond the tidal portion of their course.

Observations of the Rise and Fall of a River. Before commencing any works of river improvement, besides studying the physical characteristics of the basin, and ascertaining the normal and flood rate of flow and discharge of the river, it is necessary to find out, as nearly as practicable, the lowest level to which the river is liable to fall and the greatest height to which it may rise. As such observations, to be accurate, must extend over a series of years, it is frequently only possible to obtain the necessary information from local inquiries; but as soon as a river is placed under any sort of jurisdiction, standard gauges, referred to some common datum, ought to be established, at suitable points, and daily readings recorded, so that reliable statistics on the rise and fall of the river may be gradually collected.

Registers of this kind are kept on several of the rivers in France; and in some places the changes in level have been made self-registering, by means of a float with suitable apparatus attached for recording its movements on a revolving cylinder, which enables a continuous record to be accurately formed.

Highest and Lowest Water-Levels. There are three levels of the water in a river which it is specially important to note, namely, the highest known level, the highest level at which

navigation can be carried on, and the lowest known level. A knowledge of the highest possible flood level is necessary so that works which must not be submerged may be raised above that level, and that due protection may be afforded to low-lying lands adjacent to the river. All works connected with the navigation of a river have to be regulated in accordance with the highest navigable level. The lowest level indicates the minimum depth of water that can exist in a river. The low-water level, however, upon which works of improvement are based, is not necessarily the lowest level to which the river may fall. The absolute lowest level of a river depends upon the combined effect of several physical causes which may not occur together, except at very rare intervals; and accordingly it is not generally advisable to provide, by more expensive works, for a very rare occurrence of short duration. The lowest ordinary water-level is usually selected as the datum below which the desired depth is to be maintained.

Minimum Depth of Channel. Cross sections of a river have to be taken to ascertain what alterations in the existing channel must be made to obtain the required minimum depth. This depth must be regulated both by the nature and requirements of the proposed traffic, and by the amount of alteration that may be necessary to procure it, which must not exceed reasonable limits. In designing the improvements of a river channel it must be borne in mind that any increase in depth and width modifies both the sectional area and the hydraulic mean depth, and consequently increases the rate of discharge and tends to lower the low-water level.

Primitive Method of River Navigation. In old times, before any alterations were made in the natural condition of rivers, the first use made of the upper portions of many rivers was to float down stream the trees felled in the forests. Next, timber rafts were made which could carry a few goods; and then small boats were attached to the rafts, which were

taken to pieces when they reached their destination. By this means the produce of the upper country could be conveyed to the lower districts; but this traffic could be only carried on down-stream, and only when there was sufficient water in the river to float the rafts over the numerous shoals met with in their course.

Stanches. Later on the idea was conceived of producing artificial floods, by damming up the whole discharge of the river for a certain period, till a considerable quantity of water had accumulated behind the dam, and then letting it suddenly escape. This was accomplished by means of stanches which consisted of spars, planks, or paddles, supported by the pressure of the water against a sill below and a movable beam above. These stanches were placed across a narrow place in the river; and a man standing on a footbridge above was able to open or close them as required. The level of the water was raised for a considerable distance above these stanches when closed, and the mass of water being set free when the stanches were suddenly opened, the boats, which had previously collected above, were floated over the shallows below. This operation of flushing, or flashing, as it is termed, was extensively resorted to on several French rivers in the earlier part of the present century, as well as on the Thames and the Severn. The stanches, however, on the Severn were removed in 1842, when Sir W. Cubitt carried out some improvement works. He has given the following description of these old stanches. 'Two substantial posts, with a bottom cross sill, were fixed at a given distance apart, sufficient to permit a boat to pass easily between them. Upon one of these posts was a beam turning on its centre, and long enough to span the opening. When the stanch was used, the boatmen turned the beam across the opening, and placed vertically in the stream a number of narrow planks, resting against the bottom sill and the swinging beam, thus forming a weir which raised the water in the stream about 5 feet

high; the boards were then rapidly withdrawn, the swinging beam was turned back, and all the boats which had been collected above, were carried by the flash over the shallows below.'[1] The stanches still existing on the Thames above Oxford are very similar, being generally closed by placing vertically square wooden bars at regular intervals against the sill, and putting against these bars, called rimers, a series of boards or paddles fastened to the ends of poles. Similar stanches existed in France somewhat more than forty years ago, closed by square spars, or needles (*aiguilles*) as they are termed. These needles were lighter, and consequently easier to handle, than the planks and paddles used in this country.

Alteration of Channel.

It has been previously pointed out that a river in its natural condition varies in width and depth; and frequently, when its bed is not composed of rocky or hard materials, it is possible to increase its depth in the shallow places by simply reducing its width. A river, in its non-tidal part, has a definite discharge which is independent of the size of its channel; accordingly, when the channel is made narrower it tends to make up for the diminution, first by an increase in its rate of flow occasioned by the raising of the water-level above the contracted portion, and eventually by scouring out its bed so as to restore its channel to its original capacity. The contraction of the channel, however, cannot be carried beyond the limit of width sufficient to allow two boats to pass; and it must not be limited merely to the length of the shallow portion, otherwise the material scoured from the shoals will only be removed to be deposited again just below the contracted channel and produce a new shoal.

Cross Jetties. Sometimes jetties projected at right angles to the banks are employed for contracting a river channel,

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. iv., p. 111.

which was the method originally adopted on the Clyde, the Tyne, the Tees, and other rivers. It used to be supposed that this was an effectual and economical method of training a river; but experience has proved that such jetties, if placed far enough apart to render the system economical, are not efficient in straightening and improving the channel. The channel tends to adopt a circuitous course between the jetties, and whilst becoming deeper opposite the ends of the jetties, it shoals in the intermediate spaces. In fact some experiments carried out on the river Loire in France showed that, after a time, the erection of cross jetties actually produced a deterioration in the river channel.

Longitudinal Jetties. Cross jetties are more serviceable in training a river if they are placed tolerably close together, but then they cease to be more economical than longitudinal jetties which are jetties or banks, carried along continuously, parallel to the stream. In several cases, as for instance on the Clyde, the ends of the cross jetties have been connected eventually by longitudinal jetties; and these jetties, or embankments, furnish the most satisfactory method of training a river.

These jetties are generally constructed of the most suitable material the locality affords. Rubble stone, chalk, slag, or other hard materials, are commonly employed in the exposed portion of the bank, which may be further consolidated, if necessary, by stakes or pile work. Where suitable material for a rubble mound cannot be easily obtained, fascine work, weighted with clay and stones and secured by stakes, is employed.

Dredging Hard Shoals. When the bed of a river is too hard to be affected by the scour of the current in the contracted channel, it is necessary to remove the shoals by dredging. It is important to distinguish these natural hard shoals from shoals formed by deposit, for hard shoals, if once removed, are not liable to reform, and if the channel is made

uniform there is no more tendency for deposit to take place there than at any other place; but if shoals formed by deposit are removed by dredging, they are certain to reappear, sooner or later, unless the channel is rectified and contracted.

Easing Bends and making Straight Cuts. Besides narrowing a river at shoals, it is sometimes advantageous to ease the curve of its channel at sharp bends, and occasionally to substitute straight cuts for one or more bends. The course of the river is thereby shortened, and its fall proportionately increased, which increases the scouring force of the current and assists in deepening the channel. Special care, however, must be taken in such cases to protect the banks, otherwise the river will gradually revert to its original course: this protection may be afforded by sods, plants, fascines, planking, pitching, or concrete. Moreover, straight cuts, though improving the depth of the channel, impede the up-stream traffic by the increased velocity given to the current; and the material scoured from the bed or banks at that part is liable to be deposited lower down, when the velocity of the current is reduced below the cut.

Introduction of Locks and Level Reaches. Though the navigable condition of a river may be much improved by the means described above, it frequently happens that the natural fall of a river is too great in places to be suitable for navigation, whilst modifications of its channel increase its velocity in other parts. Also, not unfrequently, the requisite depth is unattainable except at a cost quite disproportionate to the value of the navigation.

These difficulties in river improvement were overcome by the employment of the pound-lock. It is somewhat uncertain when this contrivance was first used, but it is believed to have been introduced about the fifteenth century on some canals in Italy. Instead of increasing the depth of the river by lowering its bed, the level of the water is raised. The river is transformed, by dams or weirs, into a series of nearly

level reaches connected by locks, whose chambers, being successively filled with water and emptied, serve to raise or lower a barge from one reach to the next. By this means the requisite navigable depth is obtained with little excavation, except at the portions of the river just below the locks and at old fords; but the banks have to be raised for a certain distance above the locks and weirs to prevent the river, when raised, from overflowing its banks. The position of the locks, and the length of the reaches, are regulated by the slope of the valley; the fall at a lock being generally made about eight to ten feet. The lock is usually placed where a river is divided into two channels with an island between, the lock being situated in one channel, and a weir, keeping up the water to the level necessary for navigation, across the other channel. If no natural division of the river occurs at a point sufficiently close to the place where a change in the water-level is desirable, a site is selected where the river makes a sharp bend, a new straight channel is excavated across the bend, and the lock is constructed in this channel. The ordinary discharge of the river follows the old channel, and flows over the weir placed in the bend. This latter arrangement, though necessitating more excavation, is preferable, as it interferes less with the original channel.

The up-stream traffic is greatly facilitated by this method of improvement, as it no longer has to contend, throughout the whole of its course, with the full velocity of the river produced by the natural fall which is now concentrated at the weirs. The intervention of locks is not, indeed, absolutely necessary for converting a river into a comparatively still-water navigation, as weirs alone were formerly employed, and are still occasionally used, for dividing a river into reaches; but locks render the ascent from one reach to the adjoining one as easy as the descent.

Canals.

The mode of treatment of a river just described is frequently called the canalisation of a river, for, with the exception that the river still serves for the discharge of the rainfall of the district, it resembles a canal. In fact canals are artificial water channels made for the purpose of navigation, or for conveying water for irrigation, water-supply, or other industrial purposes.

Drainage canals form a sort of intermediate link between rivers and canals, for, though they are artificial channels, their primary object is to discharge the rainfall of the adjacent lands where the natural watercourses are insufficient or defective, whilst they are also sometimes utilised for navigation.

Navigation canals consist of a series of level channels connected by locks. The width in most parts should be sufficient to allow two boats to pass easily. If the channel was only made of just sufficient size for the passage of a boat, the resistance experienced in drawing the boat through the water would be considerable. In order that this resistance may not be materially greater than in drawing along a boat in a large expanse of water, it is necessary, according to Professor Rankine, that the width at the bottom of the canal should be twice the greatest breadth of a boat, the depth 1 foot 6 inches more than the maximum draught of a boat, and the sectional area of the waterway six times the greatest midship section of a boat.

Works for Canals. The works for a canal resemble those which have become so familiar in the construction of railways. Thus canals have to traverse high ground in cuttings; to be carried across valleys on embankments; to have bridges for the passage of roads under or over them, and to pierce hills in tunnels. These kinds of works have been so much more extensively carried out on railways, of late years, than on canals, that an adequate description of the more recent works belongs

mainly to railway engineering; and the best examples would have to be selected from railway practice, which is outside the limits of this treatise. Some differences, however, in the method of carrying out these works on railways and on canals must be noticed.

Whereas a railway is laid out with a variety of gradients, with level portions only where the lie of the country is suitable, a canal has to be made in a series of level lengths, with abrupt variations in level between them which are surmounted by locks. Greater care has, accordingly, to be taken in laying out a canal, as it cannot follow so closely the undulations of the land as a railway can; and it is therefore necessary for it to wind along the contour lines of the slopes of a valley, or to keep in the bottom, so as to avoid as far as possible changes of level, except where the natural fall of the land necessitates an alteration in the level of the canal and the introduction of one or more locks.

When a canal is excavated through porous soil it has to be made watertight by a lining of clay, concrete, or other suitable material. The cheapest portion of a canal is where the canal is made partially in cutting, with just sufficient excavation for forming suitable side banks. These banks have to be brought up carefully in layers, and to be made watertight by a puddle wall in the centre, from two to three feet thick, going down a little into the solid ground. The whole channel requires most carefully lining when it is placed on an embankment, to avoid leakage; and special care must be taken in forming the embankment to prevent subsequent settlement.

The bottom of a canal is made flat, and the side slopes are generally made not steeper than 1½ to 1; but vertical masonry side walls are adopted for passing through towns, to economise space. Through tunnels and deep cuttings the canal is generally made only just wide enough for a single boat, and

if the distance is long, passing places are provided at suitable intervals.

A towing path is formed along one side of the canal, about two feet above the water-level, and it is slightly inclined away from the canal so as to afford a better foothold for the horse drawing the barge.

Bridges over canals have been frequently made of only just sufficient span to allow of the passage of a single barge; and in many instances in this country the approaches to the bridges have been suffered to be made unduly steep.

Bridges under canals, or aqueducts as they are commonly called, resemble ordinary bridges, with the exception, that the superstructure has to be made suitable for containing the water channel, and the side walls of the superstructure, taking the place of parapets, have to be made strong enough to resist the pressure of the water. One of the side walls carries the towing path, and the water channel through the aqueduct is contracted to the width for a single barge. These aqueducts have to support the constant and uniformly distributed load of the water, instead of the rolling loads which railway and roadway bridges have to bear.

Streams flowing across the line of a canal must be spanned by an aqueduct, or carried under the canal by a culvert or an inverted siphon.

Supply of Water for Canals. It is of the utmost importance that an adequate supply of water should be provided for a canal, for making good losses from leakage, evaporation, and expenditure in locking. Frequently this supply can be furnished by adjacent streams or by a lake; but when a constant adequate supply is not procurable from these sources, which is especially liable to be the case at the summit-level of a canal, an artificial reservoir must be formed, at a sufficient elevation, by placing a dam across the valley of a watercourse, which being filled in the winter is able to furnish the

necessary quantity of water to the canal throughout the dry season.

A reservoir dam varies in form and height according to circumstances: it consists of a watertight embankment of earth, with pitched slopes and a central puddle or concrete trench, or of a masonry or concrete wall diminishing in thickness from the bottom to the top in proportion to the diminution of the water pressure. The foundations of the embankment or wall must be carried down into a watertight stratum, to provide against leakage under the dam, where it is most liable to occur, being the part of maximum pressure. The ordinary and most economical position for the outlet culvert is through the dam at the deepest part of the reservoir. Great care, however, has to be taken in making a culvert under a high embankment, lest a settlement in the embankment should lead to a fracture of the culvert, and the escape of water into the interior of the embankment. Filtration of water is also liable to occur along the outer surface of the culvert, unless prevented by a coating of puddle and sometimes by a masonry cross wall in addition. The escape of water from either of these causes, unless effectually guarded against, may lead to the gradual undermining of the embankment and its ultimate destruction. Some persons consider that the only secure method of providing against these dangers is to carry the outlet culvert in a tunnel round beyond the end of the embankment.

The construction of artificial reservoirs and of their concomitant works belongs more particularly to the special branch of water-supply of which it forms a very essential part, and it is fully treated of in books on that subject; but a few observations on reservoir dams will be given in a future chapter.

Consumption of Water in Canals. The waste of water per day, by leakage in the channel and by evaporation, is estimated by Professor Rankine as equivalent to a depth of two inches over the whole surface of the canal; and the loss by the flow

of water through the canal, due to leakage at the lock gates, at between 10,000 and 20,000 cubic feet per day. The expenditure of water in locking depends of course primarily on the amount of the traffic; but locks placed singly do not occasion the same expenditure as an equal number of locks do when placed all together in what is termed a flight of locks.

At a single lock, single boats ascending and descending alternately cause less expenditure of water than equal numbers of boats in trains; whilst at a flight of locks the case is exactly reversed. Accordingly, when a long flight of locks has to be constructed, it is frequently made double, so as to have one flight for ascending and the other for descending boats; but it is advisable not to have recourse to flights of locks where they can be avoided.

M. Graëff, in his Memoir on the Marne-Rhine Canal, estimates the total loss in 24 hours at from 1·4 cubic yards to 1·8 cubic yards per lineal yard of the canal, but that for the summit-level a greater loss should be allowed for in calculating the supply required.

Introduction of the Supply. The supply of water should not be all provided at the summit-level, as, with the exception of the expenditure of water in the passage of boats, the causes of loss are equally distributed throughout the canal. Accordingly, supplies of water should be furnished at suitable points along the canal, so that the losses may be made good as near as possible to the places at which they occur.

If on the contrary the supply is all derived from the summit-level, it is very difficult to regulate the supply which must be passed through the lock sluices so as to meet the varying demands. Wherever watercourses form the source of supply their minimum discharge must be taken as the basis in estimating the amount that can be derived from them.

Different uses of Navigation Canals. Besides supplying a means of water communication in localities where rivers do not exist, canals have been also very advantageously employed for

connecting the navigation of two rivers by surmounting the water-parting of two adjacent basins at the summit of their valleys. Thus the Thames and the Severn are united by the Thames and Severn Canal, and the Mersey and the Trent and other English rivers are similarly connected.

A similar system has been extensively adopted for connecting the principal rivers in France. For instance, the Bourgogne Canal unites the Saône and the Yonne, and consequently the Rhone and the Seine; the Brière Canal unites the Loire and the Seine; a canal connects the Marne and the Rhine, and the Eastern Canal is in course of construction for establishing a line of water communication between the Saône and the Meuse.

Canals are sometimes substituted for portions of navigable rivers where, owing to peculiarities in their course or impediments in their channel, a new artificial cut affords the easiest method of overcoming the obstacles to navigation. A lateral canal issuing from one part of a river rejoins it again below the defective portion of the river channel, and the supply of water for the canal is furnished by the river.

Occasionally, when a river appears to be very unsuitable for canalisation, a lateral canal is constructed all along its valley, so as to provide a navigable channel for the district through which the river flows, and the river merely serves as a feeder for the canal. Brindley, the engineer of several of the earlier English canals, would indeed have preferred to adopt this plan in every case, as his opinion was that the use of a river was to supply water to canals. This, however, was the view of an enthusiastic advocate of canal navigation; and the choice between canalising a river or making a lateral canal is really dependent on the cost. Sometimes a river has such a rapid current, such high floods, or such a shifting course, that the cost of rendering it properly navigable would be as great as the cost of an entirely new channel. In such a case a canal would be preferable, as it has no current to impede the up-

stream traffic, and it is not subject to floods which put a stop at times to river navigation. Sometimes also, when the requirements for the traffic are small and the river is wide, it is possible to construct a canal, just adequate to provide the necessary accommodation, at a lesser cost than the works for canalising the river would entail. The objection formerly urged against the canalisation of a river, that the weirs necessary for holding up the water in summer would prevent the escape of the floods in winter, has lost its force since the introduction of movable weirs which leave the channel unobstructed when lowered in flood time.

Canals for Discharging Water. Drainage canals resemble navigation canals in their form of channel, and in being sometimes used for navigation. Their principal purpose, however, being to discharge the rainfall of the district, they are given a fall like rivers. As their discharge is proportional to their sectional area and their fall, it is important to obtain as good and as regular a fall as possible, so that the dimensions of the channel may be kept to the smallest limits consistent with affording the necessary discharge.

They generally have to be constructed through flat districts where little fall is obtainable, and under these circumstances their course should be made as straight as possible. There is in most cases little choice of route or variety of work in these canals; and the principal difficulty experienced consists in maintaining their outfalls.

Canals for water-supply and for irrigation are designed, like drainage canals, for the discharge of a certain volume of water obtained from a river or reservoir; but generally a better fall can be obtained than with drainage canals, and, especially in the case of water-supply conduits, it is frequently necessary to protect the channel from scour by a lining of pitching or concrete.

It is in designing these discharging canals that a correct formula for calculating the discharge is of vital importance; as,

from errors in the preliminary calculations, it has sometimes been found that these canals, when executed, have not been capable of discharging the requisite volume, or have produced a more rapid flow than was anticipated, to the detriment of the bed and sides of the channel.

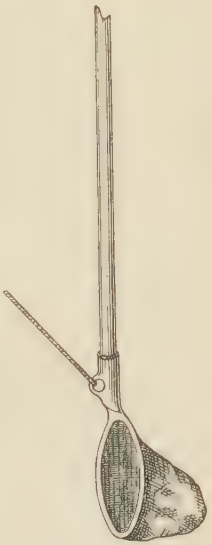
CHAPTER IV.

DREDGING MACHINES AND APPLIANCES.

Dredging. Bag and Spoon Dredger: Bucket Dredger; Hopper Dredger; Grapple Dredger; Ratchet Dredger; Dipper Dredger; Sand Pump Dredger—Type employed at Ymuiden Harbour, at St. Nazaire Harbour, at the St. Louis Bridge. General Remarks on Dredging Machines. Discharge of Dredged Material by a Chain of Buckets; direct into Wagons; through a long Shoot; by a Pump and Floating Tubes, or suspended Tubes. Excavating by Machinery. Bucket Excavator. Dipper Excavator.

DREDGING.

THE excavation for a canal or for a new cut is generally performed before the admission of the water; but the enlargement of the channel of a river or canal is usually accomplished by dredging. The term dredging is applied to excavation carried on under water by the aid of various types of machines known as dredgers.



Bag and Spoon.
Fig. 12.

Bag and Spoon Dredger. The simplest form of dredging machine is the bag and spoon dredger, which consists of a leather or canvas bag, having a circular ring of iron round its mouth, fastened at the end of a long pole (Fig. 12). A man standing in a barge holds the other end of the pole, and guides it, whilst another man drags it along the bottom by means of a chain fastened to its lower end and winding round a crab placed at the far end of the barge. The mud or gravel is scooped up by the lower part

of the ring, which is made flat, and enters the bag, which is drawn up by the chain, and the contents of the bag are deposited in the barge. The chain is then slackened, the bag is lowered to the bottom and the process repeated. This primitive plan is still employed for small operations in tolerably shallow water.

Bucket Dredger. The type of machine most commonly employed is the steam bucket dredger (Plate 1, Fig. 1). It consists of a continuous row of buckets fastened to two parallel endless chains revolving round two drums at the ends of a long beam, of which one end is fixed to a scaffolding on the barge carrying the machine, and the other end can be lowered as required by a chain attached to it, so that the lowest bucket may come in contact with the bottom to be excavated. The buckets, passing in succession along the bottom in a horizontal position, scoop up the material, and gradually revolving rise to the surface in a more upright position, and after passing round the upper drum turn bottom upwards and deposit their contents, through a shoot, into a barge placed beneath. The dredger is moved slowly either sideways or forwards during the operation, so that each bucket may have material to excavate. The steam engine on the dredger moves the buckets by causing the upper drum to revolve.

Usually the ladder of buckets is situated along the centre line of the barge, and is inclined at an angle which varies according to the depth to which the buckets are lowered. Sometimes the ladder is situated alongside the barge; and occasionally two ladders of buckets have been erected on one dredger, one on each side of the barge.

Another form of the same type of dredger has the ladder of buckets placed vertically in the centre of the barge. By this arrangement the buckets can be more completely filled, and the lifting of the material more easily performed. It is well adapted for dredging in deep water, but it is not as

suitable as the dredger with a sloping ladder of buckets for dredging in variable depths.

Hopper Dredger. Where the dredged material has to be conveyed to a distance, or into exposed situations, in order to be deposited, and also in places cramped for space and crowded with traffic, it has been found advantageous to dispense with the attendant hopper barge and combine the dredger and barge in one vessel. The chain of buckets, in this case, deposits the dredged material in the hold of the dredger: the height to which the material must be raised is thereby considerably reduced, and the vessel when loaded conveys the material to the site where it is to be deposited. The same crew and the same engine serve for working the dredger and conveying away the dredged material. The vessel being constructed with a double bow, and steering apparatus at both ends, performs its journeys to and fro without turning round. Moreover, according to some statements in a Paper on 'Dredging and Dredge Plant,' by Mr. Andrew Brown[1], it appears that the dredging operations are performed with considerably greater economy by such a machine than where the work is divided between a dredger and a steam hopper barge.

Grapple Dredger. This dredger consists of a semicylindrical bucket laid with its curved side downwards, and opening at the bottom so as to divide into two equal segmental jaws. The bucket is suspended from the end of the long boom of a derrick placed on a barge (Plate 1, Fig. 4). The bucket can be raised or lowered as desired by means of chains. It is lowered with its jaws fully extended, and when it has reached the bottom the jaws are made gradually to close, digging into the material and retaining it in the bucket in which it is hauled up. The material, thus excavated and raised, is emptied out of the bucket by merely opening the

[1] Transactions of the Institution of Engineers and Shipbuilders in Scotland, vol. xvii, p. 86.

jaws again; and the machine is then ready for another dip. The larger sized buckets can carry generally as much as five cubic yards. These grapple dredgers, which are of American invention, are capable of excavating in considerable depths of water, the smaller machines being suited for depths of from 3 to 25 feet, and the largest for depths of from 6 to 60 feet; and it is stated that, under favourable conditions, the largest class of machine can excavate 3,500 cubic yards in a day of ten hours, at a depth of 40 feet. These machines are also adapted for working in exposed situations. A special form of grapple has been made, with jaws having a powerful grip and terminated with teeth, for excavating in compact clay, for removing boulders, or for drawing out piles or other obstacles.

Ratchet Dredger. The grapple dredger, if working in loose ground interspersed with stones, boulders, or other obstacles, is liable to be prevented from closing by gripping one of these hard substances between its jaws, and then the contents fall out whilst the bucket is being raised. To obviate this defect Mr. Molesworth has designed his ratchet dredger (Plate 1, Figs. 8, 9, and 10). The bucket of this dredger is rather larger than a semicircle in section, and has unequal jaws. By a ratchet arrangement, fully described and illustrated in 'Professional Papers on Indian Engineering,' No. CXXX, the bucket, which has the slit between its jaws vertical in the act of closing, can be made to turn a quarter of a revolution in the act of being raised, so that the slit between its jaws becomes nearly horizontal. Accordingly, even if the jaws should not close completely, the material is not liable to fall out of the bucket.

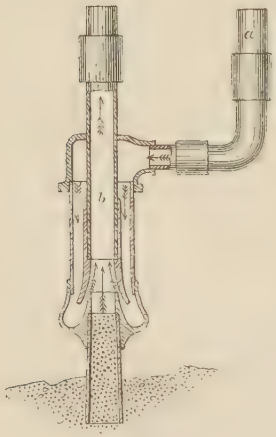
Dipper Dredger. The dipper consists of a round bucket, rather higher in front to assist in scooping up the material (Plate 1, Fig. 2). It has a capacity amounting sometimes to $2\frac{1}{2}$ cubic yards, and it is provided with a hinged movable bottom, opening downwards, so that the contents of the bucket

may be readily discharged. The dipper is hinged to the extremity of a long beam, which is moved by a derrick placed on a large barge carrying a steam engine. The dipper is also guided by chains passing over the end of the boom of the derrick. The dipper has a scope of action merely limited by the length of beam and the extent of projection of the boom, so that, in large machines, it can work over a considerable area in front and at the sides without the necessity of shifting the position of the barge. These machines, which were invented and are much employed in America, are adapted for excavating material, varying in compactness from loose rock to silt, in depths ranging from 5 to 35 feet. The larger machines are said to be capable of removing 1,200 cubic yards of silt in a day of ten hours. The dipper dredger is not suited for working in exposed situations.

Sand Pump Dredger. When the material to be removed consists of fine sand or silt it can be conveniently and economically removed by a sand pump, or suction dredger. This machine, by means of a pump, draws up the material through a pipe which has its orifice buried to a slight depth in the bottom to be excavated, and conducts the stream of sand and water combined into a barge alongside. The sand pump, employed in the entrance harbour at the North Sea end of the Amsterdam Canal during its construction, consisted of a centrifugal pump, with a fan 4 feet in diameter, and suction and delivery pipes each 18 inches in diameter, attached to an open wrought-iron framework (Plate 1, Fig. 7). One end of the apparatus was connected to timbers at the end of the vessel carrying the steam engine for working the pump, and the lower end of the suction pipe was suspended from a beam projecting from the vessel, so that it could be raised or lowered as required, and was free to follow the motion of the vessel. In working, the suction pipe tended to bury itself too deeply in the sand, and it was found to give the best results when maintained at a depth of 3 or 4 feet

below the surface of the bottom. Each of these sand pumps was able to raise about 1,300 tons of material in a day, and there were twelve employed on the works.

A somewhat different kind of machine of the same type has been employed at St. Nazaire harbour for removing sand and silt. It consists of a long screw steamboat which carries two pumps, with suction pipes attached hanging down in a slanting position, one on each side of the vessel, and connected at their ends by a perforated pipe lying horizontally on the bottom directly under the stern of the vessel (Plate 1, Figs. 5 and 6). As the vessel moves slowly along, the perforated pipe is dragged through the sand. The pumps draw the sand through the holes in the horizontal pipe, up both pipes at the sides, and the material is discharged into the hold of the vessel. As soon as the vessel is filled, it steams away to the place assigned for depositing its load. This vessel accordingly, like the hopper dredger, performs the double duty of excavating and removing the material. The perforated pipe should not be more than about 18 inches below the surface, otherwise a crust of sand forms over it and as much water as sand is drawn up. The dredging at St. Nazaire has been executed in depths ranging from 10 to 30 feet; but the machine could work with the pipes hanging vertically, which would be in a depth of more than 65 feet.



Sand Pump.

Fig. 13.

The sand pump employed by Mr. Eads, for extracting the sand from the foundations of the St. Louis bridge, acts in a somewhat different manner, as will be readily seen by reference to the annexed figure representing a section of the pump. A stream of

water is forced down the pipe *a*, and is so directed as to discharge upwards in an annular jet, over the upper end of a pipe dipping into the sand, into another pipe *b*. The jet creates a vacuum in the pipe below it, by which the sand is drawn up into the pipe *b*, and is then carried along by the upward rush of water. The pipe had a diameter of 3 inches, and discharged 10 cubic yards of sand in an hour; its length reached 100 feet. The contrivance is not strictly a pump; but the sand is extracted partly by the suction, and partly by the propelling force of the stream of water.

General Remarks on Dredging Machines. The bag and spoon dredger is still serviceable where the depth is slight, where the amount of work to be done is small and scattered about, and where funds do not admit of a large expenditure on plant. The bucket dredger is well suited for the ordinary work of maintaining a river channel, where thin layers of silt and sand spreading over a considerable area have to be periodically removed. Moreover, when the channel is narrow, and the distance to which the dredged material has to be conveyed is considerable, a hopper bucket dredger possesses advantages; but the work to be done must in such a case be large to justify the expenditure such a machine entails. The dipper dredger possesses considerable advantages over the ordinary bucket dredger in facility of manipulation; but it can only work with its full effect when excavating a layer 4 or 5 feet in thickness, and is therefore not suited for the ordinary work of maintenance. Abrupt variations in depth do not interfere with its working; and, provided it can excavate to a sufficient depth, it works more efficiently and economically than a chain of buckets, for the buckets can seldom all perform their full amount of work. Neither the dipper nor the bucket dredgers are suited for working in exposed situations, as their buckets cannot adjust themselves properly to the constantly varying level of the vessel exposed to waves or a swell.

The grapple dredger and the sand pump are the only machines capable of complying with this condition. In other respects their capabilities are dissimilar, for the grapple dredger is specially suited for excavating in rough and large material, whilst the sand pump is essentially constructed for working in sand or silt, though it has raised gravel and stones, as for instance at Lowestoft. The grapple dredger has a large capacity for work, and is capable of working in a considerable depth of water, which latter quality also applies to the sand pump.

It would be impossible to make a fair comparison of the relative cost of the different methods of dredging, except where different types of machines have been employed to perform precisely similar work; and even in such a case the work would generally be better suited to one machine than to another. However, such a comparison has been made in the case of dredging with bucket dredgers and with sand pumps at the Amsterdam Canal works. The total cost per cubic yard, including 10 per cent. of the cost of the plant, amounted to $8\frac{1}{3}d.$ with the bucket dredgers, and $7\frac{1}{4}d.$ with the sand pumps. These prices include the cost of transport to the place of deposit. In this case it is clear that the sand pumps had the advantage; and, moreover, the first cost of the plant, per cubic yard dredged, was about one-fourth less in the case of the sand pumps.

The actual cost incurred at St. Nazaire harbour in dredging with sand pumps and depositing amounted to $1{\cdot}7d.$ per cubic yard, and even doubling this, which it is considered would be required to allow for the cost of the plant as well, it would only be $3{\cdot}4d.$ per cubic yard, which is considerably less than similar work at the Amsterdam Canal. It does not, however, necessarily follow that the St. Nazaire sand pumps were more efficient than those at the Amsterdam Canal. The cost of wages, the cost of fuel, the distance to which the material is to be conveyed, the number of days during which work can

be carried on, the nature of the material, the amount of excavation within a certain space, and other matters, all more or less affect the result. The cost of dredging, accordingly, varies considerably in different localities; and the type of machine most advisable to be employed depends upon the nature and extent of the work required to be executed.

Discharge of Dredged material.

The actual cost of dredging depends upon two distinct operations; first, the cost of excavating and raising the material to the surface; and, second, the cost of conveying it to its destination. It has been already indicated that in certain circumstances economy may be attained by accomplishing both operations with the same dredging vessel, as in the case of the hopper dredger and the vessels used at St. Nazaire. Under ordinary conditions the dredged material, after being deposited in barges or punts alongside, is conveyed in these boats to its destination, where it is either discharged in deep water through a movable bottom in the barge, or deposited on the banks by manual labour.

Discharging by a Chain of Buckets. The cost of emptying the barges by manual labour is necessarily large, and if the material is very soft the operation is difficult. Accordingly, on the Danube regulation works, at Vienna, the material was removed from the barges by a chain of buckets, similar to those employed in bucket dredgers, supported on a staging on the bank, and discharged into wagons running on to the staging.

Discharging direct into Wagons. Another plan of economising the process of removal of dredged material, recently adopted in France, consists in discharging the material, brought up by the buckets, direct into wagons placed on the barges, instead of into the barges themselves. By this means, having provided a suitable landing stage, the wagons on reaching the shore can be at once run off on to a line of way,

thus dispensing with the double shifting of the material necessitated by the ordinary processes. A saving of 2*d.* per cubic yard was effected by this system.

Discharging through a Long Shoot. Where the dredged material has only to be conveyed a short distance to the side banks, special contrivances have been adopted with great advantage. Thus on the Suez Canal Works, long shoots were employed for conveying the dredged material, as it fell from the buckets, away to the banks. The shoots were made as much as 230 feet in length (Plate 1, Fig. 3). They were semi-elliptical in section, 5 feet wide. They were hinged to the dredger to admit of alterations in their inclination, which were accomplished by raising or lowering the supports on the lighter between the dredger and the bank. Mud was carried away with hardly any inclination of the shoot; sand mixed with water was conveyed away with an inclination of 1 in 20; but in dealing with sand and shells, or clay, a pair of endless chains were employed, together with a stream of water, for dragging the material down the shoot.

Discharging by a Pump and Floating Tubes. The material dredged from the sandy bottom of Lake Y and Wijker Meer, in constructing the Amsterdam Canal, was discharged on to the side-banks by mixing it with water and forcing it, in a semi-fluid state, through long wooden tubes floating on the surface of the water. A Woodford pump, 3 feet 6 inches in diameter and performing 230 revolutions per minute, was fixed to the side of the dredger at the level of the water, having a reservoir at the top in which the dredged material falling out of the buckets was received, and an inlet at the bottom for admitting the water. The material, mixed with water, was forced by the pump through the tubes, which were 15 inches in diameter and were buoyed up by floats on the surface. The line of tubes, connected together by leathern joints, extended in some cases to a distance of 300 yards;

and the material could be delivered 8 feet above the water-level. Two large dredgers were thus enabled to excavate and deposit on the banks about 1,300 cubic yards per day of 12 hours, at a cost of about 2*d.* per cubic yard.

A somewhat similar method was adopted on the Ghent and Terneuzen Canal for conveying sand and silt, dredged from the bottom, to the banks. The material, mixed with water, was forced by a pump through a tube; but the tube was supported on the dredger at one end, and its far end was held up by wire ropes passing over the jib of a crane fastened to the dredger. The tube was 60 feet long, with an inclination downwards towards the bank of 1 in 20, and delivered the material at a height of 13 feet above the water-level.

Excavating Channels and Foundations.

Dredging frequently affords the cheapest method of deepening a channel, and sometimes also of forming it, as in constructing the Amsterdam Canal through Lake Y and Wijker Meer. Occasionally, however, it is found more expedient to dam off a portion of the channel, and, after pumping out the water, to excavate it in the usual way. In preparing also the foundations for locks or other works it is generally advisable to shut off the water, as the excavation for the foundations is performed with greater accuracy in the dry; and in most cases the exclusion of the water from the site is sooner or later required for putting in the foundations.

Bucket Excavator. When the amount of excavation is very large, machines have been employed instead of manual labour. Thus an excavator was employed on the Suez Canal works, which carried an excavating apparatus like the chain of buckets of a dredger, and moved on wheels like a locomotive, being propelled by one steam engine whilst another worked the buckets. Seven of these machines excavated about eight million cubic yards on the Suez Canal; and

similar machines have since been used by their designer, M. Couvreux, on the Danube regulation works, and on the Ghent and Terneuzen Canal. One of these excavators can, on the average, excavate over 3,000 cubic yards in a day.

Dipper Excavator. A similar adaptation of dredging appliances to excavation on dry land has been made by the Americans. They have used an excavator, for working in cuttings, which is similar to a dipper dredger, with the simple modification of being made to run on wheels instead of being supported on a floating barge.

CHAPTER V.

FASCINE WORK: PILES, AND COFFERDAMS.

Fascines: Construction. Used in the form of Mattresses in Holland and in the United States. *Piles*: Bearing Piles. Sheet Piles. *Pile-Driving*. Pile-Engine, Nasmyth's Pile-Engine. Gunpowder Pile-Driver. Pile-Driving by the injection of Water. *Cofferdams*: Ordinary Cofferdams. Segmental Cofferdams. Circular Cofferdam in Lake Y. Single-sheeted Cofferdams. Closing by Panels. Wrought-iron Caisson Cofferdam for the Thames Embankment. General Remarks.

FASCINES.

Construction. Fascines consist of bundles of sticks, or of brushwood, bound firmly together. The best material for fascines is willow, with which small proportions of ash and alder are sometimes intermixed; but fascines of oak and hazel are also employed. The fascines should be used within a year after the wood has been cut, as if they are kept longer their strength and toughness diminish considerably. The Dutch, who have been compelled to resort to an extensive use of fascines in embankments and river works owing to the absence of stone and timber in Holland, devote a considerable portion of low-lying land to the culture of willows and osiers which are cut down every three or four years to be made into fascines. The ordinary fascine, which is called 'ryshout' in Holland, consists of a bundle of five or six sticks, with their branches and twigs, bound together towards each end by an osier. The sticks are from about 7 to 11 feet long, and the bundle averages about $1\frac{1}{4}$ feet in diameter.

Fascine Work. The fascines are kept in position by stakes or pegs, and by being weighted with stones, bricks, or clay.

They are frequently employed, in the form of large mattresses, at the base and sides of large embankments where the foundations and the material composing the bank are soft. These mattresses, called 'zink-stukken,' or sinking pieces, by the Dutch, consist of three or more layers of fascines, enclosed by bands of fascines intertwined together and arranged crosswise so as to form a network below and above the layers of fascines; and stakes are driven into the interstices of the upper network, and round the edge of the mattress, and are connected by bands of interwoven sticks. The mattress is towed into position, and is then sunk by being loaded with stones. The Dutch call the bottom mattress 'grondstuk,' or ground piece.

These mattresses are very useful in diminishing the amount of settlement of a bank on a very soft bottom, or at any rate in rendering it more uniform; and they serve to form steep mounds on each side of an embankment for retaining the central filling. A section of the Schellingwoude Dam, formed across Lake Y in the construction of the Amsterdam Canal, illustrates these uses of mattresses (Plate 2, Fig. 1).

Fascines are constantly employed for protecting banks from the erosive action of currents and the wash of waves.

Fascines have also been largely used by the Dutch in constructing dykes for protecting their country from the sea; but it is only within the last few years that they have been introduced into exposed works stretching out into the open sea, as at the Hoek-van-Holland jetties at the mouth of the Maas, to which reference will be made hereafter (Plate 2, Fig. 2). These jetties consist of a series of mattresses, each about 55 yards long by 26 yards broad and 20 inches thick, weighted with about 10 cwt. of stone per square yard, which are held in place by five rows of piles going through the mattresses and penetrating about 12 feet into the sandy bottom.

Mattresses of fascines are being used on a large scale in the United States for dams across rivers, and for training walls;

and they serve to form the jetties for guiding the South Pass of the Mississippi into deep water in the Gulf of Mexico (Plate 21, Figs. 3, 4, and 5). These jetties are formed of willow mattresses, 100 feet long, 2 feet thick, and varying in width from 40 feet at the foundations to 20 feet at the top, and weighted with stone. The jetties have been consolidated by large concrete blocks and pitching. It is sufficiently evident from these facts what an important place fascine work occupies in river works.

Durability of Fascine Work. Fascines, which if exposed to the weather would soon rot, are fortunately protected by the coating of sand and silt which soon accumulates in their interstices and envelopes them. They have not been sufficiently long established in the jetties at the mouths of the Maas and the Mississippi to enable an estimate to be formed of their durability in exposed situations. It was, however, considered in the case of the Maas jetties that the elasticity of the fascine work would be favourable to the maintenance of the works against the shocks of the waves. It is believed that the Mississippi jetties, with the exception of a small portion of the outer ends, are already sufficiently protected from the attacks of the worm by the covering of silt and shells with which they are incrusted.

Piles.

Piles. Piles are extensively used in river and canal works, for the construction of cofferdams, for the preparation of foundations, for the protection of banks, and for the formation of jetties and quays.

A pile, which is generally formed of squared timber, has an iron hoop placed round its head to prevent its splitting in driving, and is furnished at its lower extremity with a pointed iron shoe to facilitate its passage through the ground. The timber usually employed for piles is fir or elm, which should be free from cracks, knots, or other defects, so as to

ensure its being capable of being driven to the full extent without injury. The shoe is generally made of cast-iron, varying in weight according to the nature of the soil in which the pile is to be driven, and it is fastened to the pile by straps, the pile being tapered at the end to receive the shoe.

Bearing Piles. Where the ground on which a wall or other structure is to be erected is too soft to support the weight, piles are driven, at certain intervals apart, to consolidate the ground and bear the weight of the structure. The distance they are placed apart depends upon the nature of the soil and the weight to be borne, but generally it is about 3 or 4 feet. The piles are driven, when practicable, down to a hard stratum below the soft ground, as then their power of supporting a load is about five times greater than when held up by friction alone in soft ground.

Sheet Piling. This term is applied to a row of piles driven close together so as to form a sort of continuous sheet of timber for enclosing foundations or excluding water. They are generally driven in the intervals between a series of guide piles, placed a few feet apart, which serve to mark out the line and, being driven deeper, add strength to the line of sheeting. The sheet piles are of a thickness varying, according to the work required of them and the soil into which they are driven, from planks $2\frac{1}{2}$ inches thick to whole timbers. They are made wedge-shaped at the bottom, with their bottom edge slightly inclined from the horizontal so that each succeeding pile as it is driven may tend to close up tight against its neighbour. Heavy wedge-shaped cast-iron shoes are used where the ground is hard or large piles are employed.

Pile-Driving.

Pile-engine. The ordinary method resorted to for driving piles consists in raising a heavy weight vertically in the air above the pile to be driven, and then dropping it on to the head of the pile. A wooden framework, with timber guides

in front, supports the tackle required for raising the weight, and guides it in its descent. The weight, which is made of cast-iron and weighs from about half a ton to a ton, is called a ram or monkey. It is raised by a rope or chain to heights varying from a few feet to 30 or 40 feet; and the catch holding it comes in contact with an obstacle, adjusted at the required height, and releases the ram. The ram used formerly to be raised by men pulling at a rope which was then let go. Then a windlass was introduced, worked by men, horses, or a steam engine. Lastly, an endless chain driven by a steam engine has been used for raising the ram, which enables the blows to be dealt as quickly as the distance of the fall admits of.

Nasmyth's Pile-engine. This machine is specially suitable for driving piles in sandy soil. A heavy iron frame, containing the hammer or ram, rests on the top of the pile, and the hammer, worked by a steam engine, deals blows in very rapid succession on the head of the pile. The weight resting on the pile, and the rapidity with which the blows follow one another, prevent the jumping up again of the pile after each blow, so common an occurrence in sandy soil when a pile is driven by the ordinary method, though the force of each blow of the hammer is much less than the impact of the falling weight. From numerous comparative experiments it is evident that the rate at which the blows, 60 to 80 per minute, are given by the Nasmyth pile-engine reduces the frictional resistance of the pile by keeping the pile and the adjacent soil in almost constant motion; whereas the interval between the blows with an ordinary pile-engine allows the natural adherence between the pile and the soil to be re-established after each blow. Accordingly, in many cases, the Nasmyth machine can drive a pile farther down, more economically, and with less injury to the pile, than an ordinary pile-engine.

Gunpowder Pile-driver. The employment of gunpowder

in the operation of pile-driving was introduced in America by Mr. Shaw. A cast steel cap, called the mortar, is fitted on to the top of the pile: it has a hollow at the top into which a cartridge, containing about ten drachms of gunpowder, is thrown, which explodes on the falling of the ram, and by its explosion both projects the ram into the air and, by the reaction, assists the ram in driving down the pile. As soon as the ram rises into the air another cartridge is thrown into the mortar, to be exploded in its turn by the descent of the ram, which is kept in a straight course by guides. The raising of the ram after each blow is thus dispensed with; and the method has proved efficient, rapid, and economical. The best rate of working is about twelve blows in a minute, as the cartridges cannot well be introduced more rapidly, and even if they are, they are liable to explode at once from the undue heating of the mortar or from the ignited remains of the former cartridge. When this happens the cartridge is wasted, and the ram has to be raised by manual labour.

Pile-driving by the Injection of Water. It has been already observed that the effect of the Nasmyth machine is due to the prevention of adherence between the pile and the ground. A similar diminution of adherence, and consequent reduction of friction, in driving piles in sand, has been obtained by a different method. Two pipes are led down a pile, one on each side, their orifices being about a foot below the point of the pile. Water is injected through these pipes under pressure, and the jets thus produced, under the foot of the pile, loosen the ground below and around it, causing the pile to meet with much less resistance in driving. This plan was adopted at the Calais harbour works with most satisfactory results; a number of piles having been driven in this manner in about one eighth of the time ordinarily required.

Cofferdams.

Timber Cofferdams. Dams for excluding water from a particular site are sometimes formed of a bank of clay, or other suitable material, brought up in layers and consolidated so as to be watertight. Frequently, however, want of space or of material prevents a sloping bank being adopted, and a watertight wall of clay is supported and enclosed between two close rows of sheet piling, forming the structure known as a cofferdam (Plate 2, Fig. 3). Experience has shown that a width of from three to five feet is amply sufficient for the clay wall, as a wider wall has a tendency to dry and crack and cease to be watertight. The cofferdam is strengthened by one or more rows of horizontal walings placed outside both rows of piles. The walings on each side are generally bound together by tie bolts passing through them and through each pair of guide piles on opposite sides of the cofferdam. These tie bolts assist in resisting the outward pressure of the clay; but they are a source of some inconvenience, as leaks are liable to form along them from the settling of the clay, unless the clay is occasionally packed round them again. Care also must be taken to provide them, at each end, with large washers of hard wood, otherwise the pressure on the bolts is liable to split the walings. Cofferdams are frequently supported by struts and mounds of earth on their inner side.

Segmental and Circular Cofferdams. Sometimes cofferdams are given the form of a segment of a circle, which, provided the radius is not very large, adds considerably to their strength. In these cases laminated walings, consisting of three or four layers of planks, are adopted so that they may be bent to the curve of the cofferdam. One of the most notable instances of the kind was the circular cofferdam, 525 feet in diameter, erected in Lake Y near its junction with the Zuider Zee, for the purpose of excluding the water from the site of the Zuider Zee locks of the Amsterdam Canal during their construction.

This cofferdam was composed of two concentric rings of sheet piling, with a space of 6 feet 6 inches between them which was filled in with clay carried down a little distance below the original bottom and up to high water (Plate 2, Fig. 3). The outer row of piles and the guide piles of the inner row were whole timbers, but the sheet piles of the inner row were 8 inches thick. The piles were driven a considerable depth into the soft bottom; and two rows of walings were carried round on each side of the dam, which was supported on the inside by a mound of sand heaped against its inner face. Tie bolts were employed for connecting the two rows of piles.

A singular accident occurred with this cofferdam, owing to a sudden fall of the water outside, caused by a strong south-west wind, whilst the cofferdam was full of water. Before the water inside could be let off a difference of level of 7 feet was produced, so that there was that head of water exerting a pressure outwards, the very reverse to that which the cofferdam had been designed to support. This naturally somewhat disturbed the piles and drew out the walings, but not sufficiently to produce leakage; and when the water was eventually pumped out, and the pressure came from the outside, the cofferdam was tightened up again.

Single-sheeted Cofferdams. Sometimes in cofferdams one row only of piles is carried up to the full height necessary for excluding the water, being carefully calked, or grooved and tongued with strips of sheet iron, to make their joints watertight. A single row of sheet piling, rendered thus watertight and strutted, was able to exclude 23 feet depth of water at the Custom-house quay of Rio de Janeiro; but in such a case it is necessary that the holding power of the soil on the embedded portion of the piles should be sufficient to counteract their tendency to flotation.

Closing Cofferdams. When a cofferdam has to be closed in a tideway, the final operation of closing the openings, left

for the flow and ebb of the tide during construction, has been satisfactorily performed by lowering large timber panels sliding in grooves at the sides. This was the method by which the cofferdam erected across the Middle Level drain, after the failure of the St. Germains' Sluice, was closed[1]; and a similar plan was subsequently adopted for closing one of the cofferdams at the Portsmouth Dockyard extension works[2].

Iron Caisson Cofferdam. Wrought-iron caissons were used, instead of timber cofferdams, in the construction of a portion of the Thames Embankment (Plate 2, Figs. 4 and 5). The caissons consisted of a series of pairs of semi-elliptical rings which when joined together formed an elliptical cylinder, 12½ feet long and 7 feet wide[3]. The lowest ring of each caisson was of cast-iron, with a cutting edge at the bottom so as to facilitate the process of sinking. The caissons were placed in line lengthways, and a watertight junction was effected. Half rings were used at the upper part of the dam; and the caissons were supported by struts at the back. The advantage of this system was that all the rings above the level of 8 feet below low water could be removed, as soon as the wall had been built up behind, and used again. The lower portions of the caissons were left in place, and filled up with concrete before the foundations of the wall were commenced, and afforded additional strength to the foundations.

General Remarks. In reviewing the contents of this chapter it is worth noting that fascines are specially valuable where there is a scarcity of timber or stone, and where sandy or silty foundations have to be contended with. Fascines being light, and being only weighted with just a sufficient amount of clay and stone to sink them, press as lightly as possible upon the soft bottom; and, whilst being buried sufficiently in the sand to be secured from decay, bind together and consolidate the sand they enclose.

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxii, p. 500.
[2] Ibid vol. lxiv, p. 181. [3] Ibid. vol. liv, p. 12.

In pile-driving, a heavy weight with a small fall produces more satisfactory results than a greater fall with a lighter weight, and is less injurious to the pile. The great advantage gained by the diminution of the adherence of the ground to the pile is made evident by the results obtained by the rapid blows of Nasmyth's pile-driver, and by the loosening of the soil by the water-jet.

The kind of cofferdam that should be adopted depends much on the nature of the soil and the works. The system of iron caissons successfully employed on the Thames Embankment works, at Sir Joseph Bazalgette's suggestion, would have been too costly for a small work where the caissons could not have been utilised several times in succession.

The employment of the segmental form of timber cofferdam depends upon the space available. The circular form was particularly suitable at Schellingwoude owing to the form of the foundations for the Zuider Zee locks and sluices; and had not the difficulty in procuring timber of sufficient size tempted the contractors to use a smaller thickness of piles for the inner row, and had not the unexpected accident referred to occurred, the cofferdam doubtless would have proved most satisfactory.

The strength of a cofferdam, moreover, must be somewhat proportioned to the amount of damage or delay that might result from its failure. It is wise economy to use good timber for cofferdams, though merely temporary constructions, as the driving is a severe trial to the timber, and much of the timber, if sound, can be used again; whilst unsound timber not only gives much trouble in constructing the cofferdam, and is liable to endanger its stability, but also is worthless after it has been once driven and extracted.

CHAPTER VI.

FOUNDATIONS.

Borings. Pile-work Foundations. Well Foundations in India; at St. Nazaire; at Glasgow. Broad Foundations; Concrete; Mattresses; Cribs. Concrete Foundations; deposited under Water. Compressed-Air Foundations; at the Antwerp Quays. Underpinning Foundations. General Considerations. Foundations on Rock; Gravel; Silt; Sand; Clay.

REFERENCE has been made in the previous chapter to the means by which water may be excluded from the site of works during their execution. In the present chapter it is proposed to consider the various methods by which the foundations of locks, quays, and other river and canal works, are carried out, either with or without the aid of the preliminary works already described.

Borings. The nature of the foundations must necessarily depend upon the nature of the soil upon which it is proposed to lay them As, however, it is important to ascertain the nature of the soil before the foundations have been excavated, so that suitable designs may be prepared, borings are frequently made with this object. By means of borings, at convenient intervals, it is possible to form an approximate geological section of the ground underlying the site of the works. Unfortunately borings, whilst giving a very fair idea of the thickness of any particular stratum and the precise depths at which a change of soil occurs, do not furnish equally reliable indications as to the actual consistency of the soil. The samples brought up to the surface, besides being crushed by the boring tool, are liable to be so stirred about with water in the process of boring that their actual condition 'in situ,' in the case of

clayey and silty soils, is not readily distinguishable. A trial pit is accordingly sometimes dug, when the excavations are somewhat advanced, from which the actual condition of the soil in the particular spot is determined with certainty; but the necessity of keeping such a pit dry during the sinking renders such a course expensive and not readily available. Accordingly, in a general way, where the area of the works is large, borings are resorted to, unless the nature of the ground is sufficiently known from previous works or other sources of information.

Pile-work Foundations. It is of course advisable, when possible, to carry the foundations down to the solid ground; but not unfrequently in rivers and estuaries with alluvial beds the thickness of soft soil is too great to admit of this method being adopted. The employment of piles for consolidating the soil and supporting the foundations has been already alluded to. Where the piles do not pierce through the soft stratum and reach firm ground, their supporting power depends on the amount of solidity and tenacity possessed by the soft stratum, and varies with the surface of the pile, that is with its length and circumference. The amount which a pile is driven by the final blow of a ram of known weight falling a certain distance, has been adopted by some persons as a measure of the sustaining efficiency of the pile[1]; and formulæ have also been made for ascertaining the safe load[2]. In order to distribute the load evenly over the bearing piles, walings are commonly fastened to the upper ends of the piles, connecting them together, and sometimes planking is laid on the top. This latter addition is, however, inexpedient for the foundations of quay walls, as there is an absence of

[1] A rule frequently adopted in America is as follows:—A pile will carry, without danger of further subsidence, as many times the weight of the ram as the distance which the pile is sunk by the last blow is contained in the distance the ram falls in making the blow, divided by eight.

[2] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxvii, p. 275, and vol. xlii, p. 216.

connection between the wall and the foundation and therefore sliding forward is more liable to occur. It is better to excavate a portion of the ground between the bearing piles and fill up the space with a layer of concrete, which both binds together the piles and can be connected with the wall above.

Where the ground is very soft, or where scour is liable to occur, the foundations may be encased with advantage within sheet piles, which prevent the escape of the silt or mud sideways when weight comes on it, or the removal of silt or sand from under the foundations by the action of the current. Thus the foundations of lock walls are frequently enclosed in sheet piling to provide against the undermining influences of differences in head of water; and sheet piling is carried under the line of the sills with the same object.

Well Foundations. Another method of obtaining a solid base, without excavating the whole of the soft soil, is by sinking well foundations, which act on the same principle as bearing piles. An annular timber framework forms the base of the well, upon which rings of brick or stone are built forming a hollow cylinder or well. As the soil is excavated at the bottom the well sinks, and additional courses are added. The excavation is accomplished under water by means of a 'jham' or an excavator[1]. As soon as the well has reached the required depth it is filled up with rubble, concrete, or masonry, and the superstructure is erected upon it. This system has been in use for a very long period in India, and it has been employed for forming the foundations of some of the largest weirs constructed across rivers in that country for purposes of irrigation. A series of wells placed side by side serve, like sheet piling, to prevent undermining, and form at the same time a foundation for a wall.

The most recent instance of the employment of well

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxviii, p. 325.

foundations in Europe is at the Port of Saint Nazaire on the right bank of the mouth of the river Loire. Some new quay works, just completed, had to be carried across an old watercourse filled with alluvial deposit from the Loire overlying rock. Where the depth of the silt exceeded 13 feet the wall is built on masonry wells, sunk down to the rock, filled in solid, and connected by arches on the top. Brick wells have been adopted for the foundation of the Plantation Quay at Glasgow; they have an external diameter of 12 feet, and were sunk close together in a continuous line.

Broad Foundations. Sometimes a sufficiently firm foundation may be obtained by enlarging the bearing surface. This is usually attained by depositing a broad layer of concrete to form the base of the structure; but, as already noticed, in structures where a certain amount of settlement is immaterial, as in the jetties at Hoek-van-Holland, and at the mouth of the Mississippi, the same object is accomplished by fascine mattresses. By thus reducing the weight on a unit of area the soft soil may be enabled to support the required load.

The soil may also be consolidated, and the foundations extended, by a mass of rubble stone.

In America wide cribs of timber filled with rubble stone are extensively used for forming the foundations of breakwaters and piers on sandy and silty ground, at the mouths of rivers flowing into the large inland lakes of that country. The cribs are floated out into position, and are then sunk by filling them with stone.

Concrete Foundations. Concrete is one of the most useful materials for foundations. It can be adapted to any irregularities of the bottom, it can be rapidly prepared and put in place, and can be made of any thickness or shape. By making it with hydraulic lime or cement it can be safely placed in foundations from which water cannot be conveniently excluded for any length of time; and, with proper

precautions, it can even be deposited under water, or where a stream of water runs across the foundations.

The points necessary for the formation of good concrete are—that the materials should be of good quality and clean, the sand sharp and not too fine, and that the materials, when well mixed together, should have no interstices between them which are occasioned by a too large proportion of stone. Broken stone should be used in preference to shingle, as the rough surfaces adhere better to the mortar; though shingle has usually the advantage of being clean. The concrete, when once deposited, should be disturbed as little as possible, and should not be thrown from a great height, as the advantage gained by the consolidation of the mass, due to the fall, is more than counteracted by the separation of the heavier from the lighter particles in their descent.

It is important that concrete should be exposed as little as possible to the action of water in motion, as the effect of a current or of waves is to wash away the cement; and wherever it is impossible to protect the concrete entirely from this action the proportion of cement should be largely increased, to make up for the loss that must inevitably occur. Concrete may be deposited without injury where there is a small amount of still water in the foundations. In such a case, however, it is advisable to excavate the foundations in short lengths, and to commence by depositing the concrete in a heap at one corner, gradually extending the heap and driving the water before it so as to expose as little surface as possible. If a small stream is flowing through the foundations it should be concentrated and confined within a narrow channel, which should be left open till the whole of the concrete round it has been carried up to the full height, when the channel may be filled up rapidly with concrete containing a large proportion of cement. The water will thus be effectually prevented from percolating through the concrete whilst it is setting. If there is a stream of water which must

be provided with an outlet through the foundations, it may be conveyed through the concrete by means of a pipe imbedded in the mass.

To deposit concrete under water, a shoot, or closed skip with a movable bottom, should be employed, so that the concrete may be lowered into its place with as little motion through the water as possible. The shoot is the most convenient arrangement; but for depositing in any depth of water a skip is preferable, as in such a case the materials are liable to separate in passing down the shoot, the heavier particles reaching the bottom first and collecting in a mass. It is also advisable to enclose the site with timber casing lined with tarred canvas, so that no current of water may act on the concrete during the operation.

Bags filled with concrete, as employed for the foundations of the Aberdeen Harbour breakwaters, furnish another method of depositing concrete 'in situ' under water. The covering of the bag prevents the washing out of the cement, whilst it allows the concrete to adapt itself to any irregularities of the surface and to form a compact mass with the adjacent bags.

Compressed-Air Foundations. Cylindrical foundations formed by sinking iron cylinders, either by merely weighting them in watertight soils and excavating at the bottom as though enclosed by a cofferdam, or by filling them with compressed air in porous soils and excavating inside under pressure, have been chiefly employed for the foundations of the piers of bridges. These works, however, do not properly form part of the subject under consideration, as, though bridge foundations are laid in rivers, they are not strictly river works, or works undertaken for the improvement of rivers or their banks.

There is, however, one important work of river improvement, in course of execution, where the method of compressed air has been adopted for the foundations. The improvement

of the river Scheldt at Antwerp comprises, in addition to dredging, the regulation of the right bank of the river by a line of quays, 3,800 yards in length, built for the most part in the bed of the river.

Large bottomless caissons with plate-iron sides and roof are built on shore, of a suitable length, wide enough for the foundations of the quay wall, and of sufficient height for a man to stand upright in them. This portion of the caisson constitutes the working chamber. Sides of plate-iron are erected on the top of the roof and connected by bolts. The caisson is then launched in the river, and floated into position between two barges. Tiers of stages are erected on an iron framework on each of the barges; and iron girders, placed over the caisson, connect the framework of the barges at the top. The barges carry the air-compressing machinery; the materials for the wall are placed on the stages; and the girders support the caisson, when necessary, by means of chains. The building of the wall is commenced on the top of the roof of the working chamber, and carried up till its weight is almost sufficient to counterbalance the flotation of the caisson. The caisson is then floated into its exact position, so that the wall may be in its true line. The supporting chains are drawn tight, and weight is added to the wall at high water so that the caisson may touch the bottom at low water; its position is then finally adjusted, if necessary, by help of the chains, and the wall is rapidly carried up, and weighted, if required, to prevent the caisson floating when the tide rises. The wall is then built up till the weight is sufficient to keep the caisson from floating when the working chamber is filled with compressed air. The compressed air is introduced into the working chamber through a central vertical tube round which the wall has been built. Workmen then descend into the working chamber through the air-lock at the top and down the central tube; and, after the foundations have been excavated to the required extent, the chamber is filled with

concrete passed down into it through four other vertical tubes. The wall is then proceeded with till it has been raised a little above low-water mark, when the plate-iron casing, erected on the top of the working chamber and keeping out the water from the wall, is unbolted and the plates removed to serve for another caisson, and the wall is built up in the ordinary manner. By this process cofferdams are dispensed with; and the only portion of the caisson which has to be left in the wall is the ironwork which forms the working chamber. A small interval is necessarily left between each length of wall to allow for the sides of the caisson; but vertical recesses are formed at the ends of each length, and, when the casing has been removed, planks are placed in front and at the back of the wall to close the apertures, and concrete is deposited 'in situ' between the two sections of the wall, and proper bond is secured by means of the recesses. Above low water the wall is continuous with a facing of stone, the lower portion and backing being composed of brickwork, and concrete fills up the hollows left in the first instance for the vertical tubes. This work furnishes an example, on a large scale, of the employment of the compressed-air system for laying foundations, and is being carried out with very satisfactory results, the magnitude of the work justifying the adoption of special plant which can be made use of several times in succession at different parts of the wall.

Underpinning Foundations. When a river is improved, it frequently happens that the increased depth given to the channel tends to undermine the foundations of bridges and quay walls which had been constructed at a level suitable to the original river bed. This usually necessitates, either the rebuilding of the structures, or the carrying down of the foundations by the process known as underpinning. The ground under the existing foundations is excavated in sections, and brickwork, masonry, or concrete, is introduced. The foundations have to be supported during the operation by timber

beams and props; and the filling up of the cavity made under the walls or piers has to be very completely and carefully executed, otherwise settlement will occur. Owing to the confined space in which the work can be conducted, the operation is slow and difficult, the final course having to be packed in by the help of wooden rammers. Underpinning, however, is the only satisfactory alternative course to reconstruction, and therefore a considerable expenditure upon it is justifiable.

It is sometimes feasible to protect the foundations of the walls and piers by means of sheet piling, instead of underpinning them; but it is difficult to guard effectually against the gradual washing away of the mound of soil upon which the structure stands above the bed of the river. The piers of Old London Bridge were, indeed, protected in this manner for some time, after the bed of the river had been scoured to a depth of some feet below the level of their foundations; but such a course increases the obstruction which the widened out bases of piers present to the stream, and it can only be expedient where economy demands the adoption of a temporary measure.

General considerations respecting Foundations. The foundations constitute the most important, the most difficult, and often the most costly portion of a hydraulic structure. The safety of a lock or quay wall depends upon the security of its foundations; and any repairs in a foundation are sometimes impossible, and invariably difficult to perform. In executing lock foundations it is necessary to provide against the undermining action of water due to differences in head, and also against unequal settlement where the strata dip or change abruptly. In the case of a quay wall, precautions have to be taken in addition against the sliding forward of the wall.

Rock is perhaps the best stratum for foundations to be built upon; but, where its level varies much, its unyielding

nature increases the chance of unequal settlement of the superstructure.

Gravel is a very reliable material for foundations, provided percolation and consequent washing away of the sand in it can be prevented. It has no tendency to produce settlement; it is firm, and not influenced by exposure to the atmosphere; it is readily shifted, and, if clean, forms excellent material for concrete. A considerable amount of pumping, however, is generally necessary for keeping down the water in gravel soils when the excavations are below the ordinary water-level of the district.

Silt and fine sand do not present insuperable obstacles to a good foundation; but the operations, previously described, for obtaining stable foundations in such soils entail considerable expense.

Clay, which might appear at first sight one of the best soils on which to build, is open to several objections. Some clays, which appear firm and hard when first opened out, soon change their condition when exposed to the weather and to water; they swell, break up, and become semi-fluid. Clay is also liable to contain thin layers of sand through which water can percolate, and which, if dipping, may lead to the sliding forward of the wall. The only expedient in the first case is to take out the excavations for the foundations in very short lengths, and leave the clay as short a time as possible exposed to the air. The sliding forward of the wall must be provided against by carrying down the foundations to a greater depth below the surface of the ground in front, so as to have a bank of earth against the toe of the wall as a counteracting weight, and also by putting as little weight as practicable at the back of the wall whenever such a danger is to be apprehended.

CHAPTER VII.

WORKS FOR AFFORDING A PASSAGE FROM ONE LEVEL TO ANOTHER.

Locks: Description of Parts and Construction. Flight of Locks. Lock-Gates: Description of Parts. Material: Wooden Gates, Iron Gates. Strains. Rise. Forms: Straight, Segmental, Gothic Arch. Roller under Gate: advantages and disadvantages. Methods of moving Gates. Caisson Gates: Floating, Rolling. Consumption of Water in Locking, in a Single Lock, in a Flight of Locks. Methods of saving Water in Locking: Side Ponds; Parallel Locks; Apparatus at the Aubois Lock. General Remarks.

Locks.

The introduction of locks for facilitating continuous navigation has been already alluded to in Chapter III. A lock consists essentially of a chamber, placed at the junction of two reaches, in which the water can be raised or lowered so as to be on a level with either the upper or lower reach. The lock-chamber is usually closed by a pair of gates at each end; it is filled by letting in water from the upper pool through sluices in the upper gates or side walls, and emptied by letting it out through similar sluices at the lower end. A vessel, admitted into the lock when the level of the water in the lock is the same as in the reach which the vessel has just traversed, can be thus easily raised or lowered to the level of the adjoining reach.

Description of a Lock. The parts of a lock are shown on Fig. 14 (page 82). They consist of two side walls, *A A*, with curved ends to facilitate the entrance and exit of boats; two pairs of gates, *B B*, at each end of the lock-chamber, *C*, shutting at the bottom against a sill, *D D*. The bottom of

the lock-chamber is covered by the invert, *E*, which, as its name implies, is generally made in the form of an inverted arch to support the side walls, exposed as they are to constant variations in pressure, and to secure the chamber against injury or leakage from below. The portion of the floor of the lock, *F F*, over which the gates move is called the gate-floor. Beyond the gate-floor, at each end of the lock, is the apron, *G G*, which is generally protected from scour by pitching or masonry. The vertical post on which each gate turns, called the heel-post, stands upon a stone

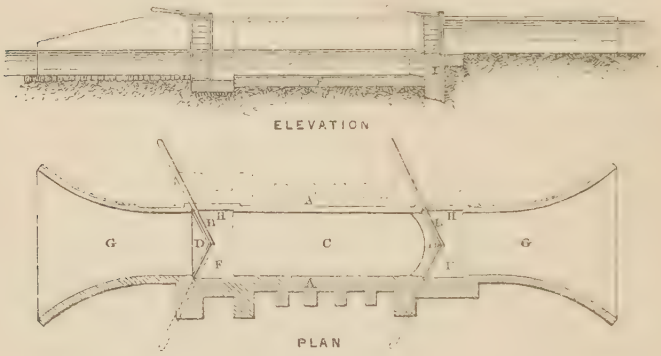


Fig. 14.

called the heel-post stone, and fits into a vertical curved groove in the lock wall, formed by courses of carefully dressed stones, which from their shape are called hollow quoins (see Fig. 15. page 86). A recess, *H H*, is formed in the lock wall, on each side of the gate-floor, into which the gate is drawn, when opened, so that it may be out of the way of boats passing through the lock; it is called the gate recess, and is terminated at one end by the hollow quoins, and at the other end by another set of dressed stones called square quoins. When sluiceways are provided in the side walls, the inlet openings of both the upper and lower sluices

are placed in the gate recesses, and the sluices discharge on to the invert and lower apron respectively.

Construction of Locks. Formerly locks were constructed of timber, or sometimes with masonry walls at each end, and merely a cutting with sloping sides for the lock-chamber, the slope being frequently terminated about the low-water level by a line of sheet piling. Timber, however, was liable to decay, and to be washed away by the rush of water from the sluices; and the sloping sides of the chamber caused a great waste of water in locking. Vertical walls of brickwork or masonry were, accordingly, eventually adopted throughout; and in large locks the invert, gate-floors, and aprons, are constructed of masonry, and the sills and hollow quoins of granite. Locks are made just large enough to admit the largest class of vessels employed on the special navigation; but where the size of the vessels varies considerably, as in docks and some canals, as for instance on the Amsterdam Ship Canal (Plate 11, Fig. 8), an intermediate pair of gates are sometimes introduced so that a shorter lock-chamber may be provided for small vessels, thus saving both time and water in locking.

In locks leading to docks, or on rivers where the fall of the bed is not abrupt, the upper and lower sills are placed at the same level; but on canals, and on rivers where the original bed is altered, the upper sill is placed on the top of the lift wall, *I*, at the level of the bottom of the upper pool, and the depth of the upper pair of gates is correspondingly reduced. When the difference of level between two adjoining reaches of a canal is considerable, a series of locks, placed close together in steps, are introduced. This flight, or chain, of locks has the advantage over the same number of single locks, placed at intervals apart, that it only requires one pair more of gates than the number of locks, instead of double that number, as the lower gates of one lock form the upper gates of the lock next below.

Lock-Gates.

The smallest locks are closed by a single gate at each end. There is, however, an advantage in closing the lower end of the lock with a pair of gates, as a single gate requires more space for opening, and thus either reduces the available length, or necessitates an increased length of lock, and a corresponding increased expenditure of water in locking. Except in small locks, both ends of the lock-chamber are closed by a pair of gates, each gate being rather longer than half the width of the passage, and meeting at an angle in the centre line of the lock opening. Each gate turns on a heel-post, and has a meeting, or mitre, post fixed at its other extremity, which, when the gates are closed, shuts against the mitre-post of the opposite gate. The mitre-posts of the two gates are formed so that their opposing surfaces may be in close contact when the gates are closed; and a horizontal sill-piece at the same time shuts closely against the sill.

Wooden Lock-Gates. Lock-gates across small locks, and in a moderate depth of water, are generally made of wood; and at the Amsterdam Canal wooden gates have been adopted for the inner gates of the locks, having a width of 60 feet; but in this instance the variations in the level of the water are slight, and consequently the pressure is moderate. Wooden gates, however, of even larger span have been erected at the Liverpool Docks; but in such cases wrought-iron gates are preferable, the heel-posts, mitre-posts, and sill-pieces being made of wood. English oak is the best material for wooden gates; but where the gates are liable to be attacked by the worm, greenheart timber must be used, though it is costly to work and liable to split.

Wooden gates are formed of a series of horizontal beams, connecting the heel-post and mitre-post; against which vertical or diagonal planking is fastened, and being made

watertight acts as the skin of the gate. The beams are placed closer together towards the bottom of the gate in order to sustain the increased pressure due to the depth of water. A section of one of the lock-gates of the Whitehaven Docks [1] shows the form of construction. (Plate 2, Fig. 6.) It is straight on the side of the sill, but curved on the outside, thus increasing in thickness towards the centre of the gate.

Iron Lock-Gates. Iron gates have generally a double skin, of wrought-iron plates, fastened to horizontal ribs or girders, and they are strengthened in addition by vertical ribs. The skin plates are increased in thickness, and the horizontal ribs are placed closer together and strengthened, towards the bottom of the gate, to allow for the increased strain. A horizontal and a vertical section of an iron lock-gate, at the West India Docks [2], indicate the form and construction of this type of lock-gate. (Plate 2, Figs. 7 and 8.)

Strains on Lock-Gates. The strains on a single straight gate shutting across a lock are very simple, as they result merely from the pressure of the head of water against its inner face, which increases in proportion to the depth. The horizontal beams of the gate act like girders, supporting an evenly distributed load which imparts a strain equal to half the whole pressure exerted at the centre.

When, however, two straight gates meet at an angle in the centre line of the lock, the strains on the gates are more complex. Each gate, besides being subjected to the water pressure on its inner face acting as a transverse strain, has also to bear a compressive strain in the direction of its length, due to the pressure of the opposite gate against its mitre-post. This latter strain is equal to half the water pressure on the opposite gate multiplied by the tangent of half the angle between the lines of the two gates when closed. Usually the projection of the gates, or as it is termed their

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. lv, pl. 5.

[2] Ibid. vol xxxiv, pl. 19.

rise, in proportion to their span is given in any description of lock-gates in preference to the angle they subtend, so as to include the case of curved gates. The rise of a pair of lock-gates is the length of the perpendicular line drawn from their meeting point to a line passing through the centres of their heel-posts. The actual projection of the gates depends upon the proportion the rise bears to the span, or width, of the lock, from which the angle subtended by the gates is readily deduced. Thus the accompanying sketch shows a pair of

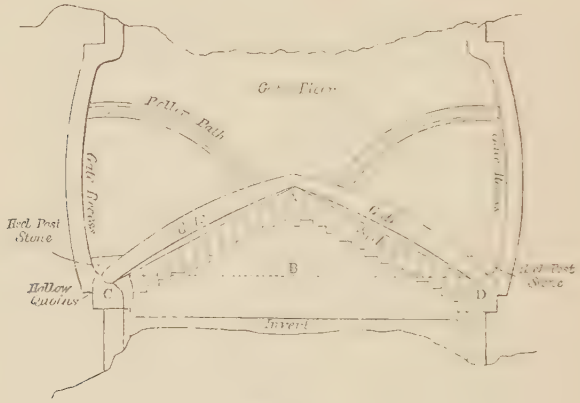


Fig. 15.

gates whose rise, AB, is one fourth of the span, CD. It will be readily seen that the tangent of half the angle CAD, referred to above, is merely $\frac{1}{2}\ CD \div AB$, or half the span divided by the rise. In the particular case, where the angle CAD is a right angle and the gates straight, the tangent of half the angle is unity, and the longitudinal compressive strain imparted to each gate by the other one is equal to half the water pressure upon one gate. It is evident that the amount of rise exercises an important influence on the strains of a gate, as the compressive strain on straight gates of the same span varies inversely as the rise. Thus in the

old Sparndam lock-gates, with a rise of only one sixteenth of the span, the compressive strain amounted to four times the water pressure on one gate. On the other hand a large rise increases the length of the gates, and reduces the available length of the lock.

Forms of Lock-Gates. Another essential element in the design of lock-gates is their form. For small gates the straight form is the simplest, and their strength is made adequate for the wear and tear and shocks they are liable to undergo in working and from boats coming against them, and not merely for bearing the small strains the water pressure brings upon them. In larger gates, however, where the pressure to be supported is the chief consideration, it was pointed out by Mr. Peter Barlow[1], nearly fifty years ago, that, theoretically, the best design was that the gates when closed should present the form of a continuous circular arc, as then the transverse strain would be completely eliminated, and the strains would be entirely compressive in the direction of the length, which is precisely the kind of strain which timber is best able to support. This was prior to the introduction of wrought-iron gates; and Mr. Barlow thinking that, besides the difficulty of procuring timber of sufficient curvature, a slight flattening of the arch composed of two separate portions might cause an injurious strain at the point of contact, proposed to make the two segmental gates meet at a very slight angle, thus giving them the form of a Gothic arch, but much more nearly approaching a true arc than the forms previously adopted on the Caledonian Canal and the docks on the Thames.

When, however, wrought-iron was introduced for the construction of lock-gates, and thereby a much greater facility was afforded for giving a curved form with ample strength to gates of large size, the objections feared by Mr. Barlow were removed; and some gates forming a continuous arc,

[1] Transactions of the Institution of Civil Engineers, vol. i, p. 74.

when closed, were erected across a lock 80 feet wide at the Victoria Docks on the Thames (Plate 2, Fig. 9). These gates were described by Mr. Kingsbury in an interesting paper, read at the Institution of Civil Engineers in 1859[1], in which he draws special attention to the advantages of what he terms cylindrical gates over straight gates in reducing, by about one half, the amount of metal required to resist the strains. Moreover, by eliminating the transverse strain, the cylindrical form of gate has the advantage of rendering the strain approximately uniform on the skins for every horizontal section, thus enabling each horizontal row of plates to be the same thickness all along the gate; and the thickness is only increased in a vertical direction in proportion to the depth, which renders it much easier to make the gates watertight. The compressive strain on cylindrical gates is the pressure on the unit of surface multiplied by the radius of curvature.

The cylindrical form has not, however, by any means been universally adopted in practice; nor have all writers on the subject of lock-gates advocated its use. The subject of lock-gates has been brought forward, in a special manner, on two subsequent occasions at the Institution of Civil Engineers, having been investigated analytically by Mr. W. R. Browne[2] and geometrically by Mr. Blandy[3] in papers which, together with the discussions on them, contain theoretical and practical information of considerable interest. Mr. Browne does not consider the cylindrical form, even theoretically, the best; he states that a considerable waste of material takes place in the ordinary form of double-skinned wrought-iron gates, and he would prefer the type of gate erected at the Bute Docks, Cardiff (Plate 2, Fig. 11), where horizontal plate-iron girders, stiffened by vertical and diagonal ribs, support a wooden skin which can be easily kept watertight and repaired. Mr.

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xviii, p. 445.
[2] Ibid. vol. xxxi, p. 317.
[3] Ibid. vol. lviii, p. 154; vol. lix, p. 2.

Blandy, whilst acknowledging the advantages of the cylindrical form, considers that a flatter curve, forming a Gothic arch, and a smaller rise than theory would assign, are expedient in order that the depth of the gate recess may be reduced.

Very deep gate recesses are undoubtedly undesirable; and for this reason, and for the sake of reducing the length of the gates, the rise is not generally made as great as theory indicates to be the best. Sir F. Bramwell pointed out very clearly, in the discussion on Mr. Browne's paper, that the most economical rise for a pair of segmental gates is approximately one third of the span, which agrees with the result arrived at by Mr. Kingsbury; but in practice a proportion of one fourth is very commonly adopted. This for instance is the proportion for the gates at the Victoria Docks (Plate 2, Fig. 9); at the South Dock, West India Docks (Fig. 15, page 86); at the Albert Dock, Hull, and at the Avonmouth Dock. Mr. Blandy proposes a rise of one sixth of the span in his typical form, which has been sometimes employed, as also the intermediate proportion of one fifth, of which the gates at Whitehaven are an instance. The objections to sharply curved gates, fitting into deep recesses, and showing a curved face in the line of the lock wall are, that vessels are liable to be injured or to injure the gates in passing through the lock, and that space is also taken up. These objections, however, would apply with most force to large gates; but it is precisely these gates that have been given the form of a continuous circular arc, in the case of the Victoria Docks, and of the Albert Dock, Hull; nevertheless, owing to the fairly moderate rise adopted, and the use of timber fenders, the form of these gates appears not to have caused inconvenience.

Assuming that the line of pressure always follows the centre line of a cylindrical gate, such a gate might be made very light; but an obstacle at the mitre-posts or at the sill is

liable to deflect the line of pressure: the gate also must be strong enough to resist in addition the shocks of vessels coming into collision with it; and the inevitable corrosion of the metal necessitates an excess of thickness. Moreover, the cylindrical form is not actually carried out even in the largest double-skinned gates, owing to the necessity of keeping the heel-post and mitre-post within moderate limits; and in the smaller gates it is imperative to make the width between the skins in the central portion large enough to enable a man to get into the gate, in order to paint it inside. Accordingly, all double-skinned curved gates bulge out somewhat towards the centre, the back of the gate being given a sharper curve than the front concave face. This increase in width at the centre of the horizontal section particularly applies to the smaller gates; and they are consequently well adapted to resist a transverse strain, and there is no objection to their meeting at a slight angle. This Gothic arch shape is in fact the common form adopted for wrought-iron gates of about 60 feet span (Plate 2, Fig. 10). Whilst, however, the front face of these gates is curved, the sill-piece is sometimes made straight by fastening a projecting piece at the bottom of the gate (Plate 2, Fig. 8, and Fig. 15, page 86). This arrangement has the advantage of making the fit between the sill-piece and the sill easier, each being straight instead of curved; but it increases the tendency to flotation when there is a head of water against the inside of the gates, and necessitates, therefore, a larger amount of ballast in the gate, which adds to the weight to be moved in opening or closing the gates.

Though gates with both faces curved are usually adopted, gates straight on the outer side and curved at the back are also erected. This type has been employed for the iron gates at the Amsterdam Canal locks; and though it renders a flatter curve more expedient for the back than where both faces are curved, yet it offers an opportunity of introducing diagonal bracing, from the top of the heel-post to the foot of the mitre-post, to

assist in supporting the extremity of the gate. Such a form of gate, moreover, both reduces the depth of the gate recess, and, when open, causes no break in the line of the lock wall. These points were of special importance at the Amsterdam Canal, as the locks are placed side by side, having common side walls, so that deep gate recesses would have necessitated a corresponding increase in the width of wall on each side; and as there are five pairs of gates in each lock it was important that, when open, they should be in a straight line with the walls (Plate 11, Fig. 8).

Straight iron gates, with parallel skins along the central portion, and with the back skin converging at the extremities towards the front, were erected at Dunkirk in 1880.

Support of Lock-Gates. The weight of a lock-gate is supported by the pivot on which the heel-post turns, by the anchor strap which encircles the top of the heel-post, and usually by a roller placed near the other extremity of the gate. The pivot is fastened to the heel-post stone, and a socket at the bottom of the heel-post fits over the pivot. The anchor strap is fastened to the anchor, formed of a cast-iron frame, in the form of a sextant, bedded into the masonry and further secured by tie bolts. A roller is generally placed at the bottom of large gates to assist in supporting the weight of the gate (Plate 2, Fig 8). Its axis is placed in the vertical plane passing through the axis of the heel-post and the centre of gravity of the gate, and the proportion it bears of the weight depends upon its distance from the centre of gravity. In straight gates, the roller is placed under the gate; but in curved gates it is partially clear of the gate, and its bearing is adjusted by means of a vertical rod over it, at the back of the gate, which is raised or lowered by a screw or wedges near the top of the gate. The roller, which is slightly conical, runs on a cast-iron roller path fixed to the gate floor (Fig. 15, p. 86).

Roller under Gate. A considerable difference of opinion exists as to the expediency of employing a roller. The roller,

besides bearing a portion of the weight of a gate, relieves the anchor strap from the strain which would otherwise come upon it, and prevents the wearing that the hollow quoin and heel-post might experience near their base if the gate tended to drop at the other end. On the other hand, the roller sometimes impedes the motion of the gate, owing to some roughness or impediment, or to some settlement or fracture of the roller path. Occasionally also it has been discovered that a roller has been for some time so much out of adjustment as no longer to bear upon its path, affording consequently no support and merely adding to the weight of the gate towards its extremity. Rollers are usually employed for gates of any size in this country, whilst on the continent they are frequently dispensed with.

In judging of this question the weight of the gate requires to be taken into consideration. Now the effective weight of a gate is not its actual weight, but its weight when immersed in water—that is, its actual weight diminished by the weight of the volume of water which it displaces. Wooden gates are naturally light under such circumstances, though their specific gravity is increased by their iron fastenings. Iron gates with watertight double skins have even too much buoyancy, and have to be ballasted with a certain quantity of water. Accordingly, the effective weight to be moved, in the case of either kind of gate, is small when immersed in a full depth of water. When, however, the depth of water in which the gates are worked varies, the weight of the gate on its supports also varies, except in the rare instances where the flotation of iron gates has been made self-adjusting. Accordingly, whereas in Holland, where there is little variation in the water-level, rollers have been dispensed with, it does not follow that the same principle might be adopted with similar advantage elsewhere.

It may fairly be concluded that, whilst rollers are unnecessary where the variations of water-level are small, it is expedient to employ rollers for large gates, and where the

variations in level are considerable, as for instance at a tidal entrance where the tidal range is large; unless some self-adjusting system for counterbalancing flotation can be introduced, or the counterbalancing weight be placed close to the heel-post, as has been recently done at the Dunkirk gates, which have a span of 69 feet and no rollers.

Methods of moving Lock-Gates. The smaller wooden lock-gates are opened and closed by pushing against the balance beam which has a heavy butt end, projecting over the side wall of the lock, and is fastened to the top of the heel-post and mitre-post, and serves to balance the gate on the pivot. The larger gates are moved by chains fastened to the gate and worked by capstans or hydraulic machinery. The employment of rollers renders it advisable to attach the chains some way down on each side of the gate, in order to facilitate the motion and to avoid straining the gate. This necessitates the construction of chain passages in the side walls for the opening and closing chains, with rollers for directing and guiding them. When the gates are constructed without rollers the chains can be attached near the top of the gate and worked from the top of the side walls, as at the Amsterdam Canal locks. A still better plan in such cases, where there is ample space at the sides, is to fasten a long, flat, toothed iron bar to the top of each gate, which opens or closes the gate on being moved by a pinion on the top of the side wall. This system is in use at the Antwerp Docks; it enables chains to be dispensed with, which are liable to get in the way of vessels and diminish slightly the available depth over the sill. It has been proposed to adapt hydraulic power to this method of working lock-gates, by attaching the piston of a hydraulic engine to the back of each gate.

Varieties in Design. It will be observed that no definite rule has been adopted, in practice, either as regards the form or the material of lock-gates. The strength, durability, convenient form, and ease of working of lock-gates, are of much

greater importance than economy of material. The cost of the gates is a small item in the cost of large river, canal, or dock works; whilst the security and facility of navigation depends much upon the gates. Accordingly, each engineer designs lock-gates of the form which he considers will be most suitable for the site and for the requirements of the traffic, and hence the varieties in the actual designs.

Wooden gates are preferred by some engineers, and iron gates by others. Wooden gates appear to be frequently as durable as iron gates; whilst iron corrodes rapidly when exposed to salt water. The Dutch, however, have preferred iron for the sea gates of the Amsterdam Canal locks, whilst the gates pointing inwards are of wood. M. Guillain, an engineer at Dunkirk harbour, comparing wooden and iron gates at that port, having the same effective weight at high water, gives the preference to the iron gates, as having a smaller effective weight at mean sea level, and therefore easier to work than the wooden ones except just at high water; but, whilst thinking that a straight iron gate, though theoretically inferior to a curved wooden one, is practically better, he would prefer a curved wooden gate to a curved iron one. This preference however for a straight over a curved iron gate is contrary to the practice in this country.

Caisson Gates.

Floating caissons have been sometimes employed for closing locks, but they are more specially suitable for closing the entrances to graving docks, which, unlike locks, are only occasionally opened and closed, and where, accordingly, the greater labour of floating a gate in and out of position is more than compensated for by doing away with gate recesses, gate floors, gate machines, and other expensive accessories. The caissons when put in place are weighted by the admission of water, which is pumped out again when the caisson is to be removed.

A peculiar form of rolling caisson gate has been erected in Holland for closing one end of a lock on the Kampen Canal, of which a description is given in the Transactions of the Society of Dutch Engineers[1]. The wrought-iron caisson runs on rollers across one end of the lock-chamber, and when the lock is to be opened the caisson runs back into a recess in one of the side walls. The caisson is so shaped, and is so closely fitted at one end to the recess, that the variation in head in the recess and outside, regulated by means of sluices in the side walls, serves to propel the caisson in or out of the recess. This apparently is a solitary example of a rolling caisson, though floating caissons, sliding into a recess in the side wall and hauled in and out by machinery, have been employed at the dockyards at Portsmouth and Malta.

Consumption of Water in Locking.

Each operation of locking withdraws a lockful of water from the upper pool in three out of the four possible cases, the exception being when a descending boat finds the lock full. It is evident that the least consumption of water is attained, in the case of a single lock, when single boats ascend and descend alternately, a single lockful being under these circumstances sufficient for two boats. In a flight of locks, however, the locking of a train of boats up and down causes less expenditure of water than an equal number of boats ascending and descending alternately. Accordingly, a flight of locks is sometimes made double, one flight being used for ascending and the other for descending boats, whereby the consumption of water is considerably lessened. On rivers, the amount of water expended in locking is generally immaterial, as the water forms merely a portion of the regular discharge which would pass over the weir if it did not pass through the lock. In canals, on the contrary, where the supply of water is limited, and

[1] Tijdschrift van het koninklijk Instituut van Ingenieurs, 1879–80, p. 265, plates 27, 28.

especially at the summit-level and where the supply is drawn from a reservoir, the amount of water expended is of considerable importance.

Methods of saving Water in Locking.

Various expedients have been resorted to for reducing the consumption of water in locking. The employment of two flights of locks, side by side, for this purpose has been already mentioned. Another plan is to provide one or more side ponds into which the upper portion of the water in a lock can be let off, so that the same water can be used again for refilling the lower part of the lock instead of being discharged at once into the lower pool. Theoretically, it would be possible, by constructing a series of side ponds at different levels, to save a large portion of the water; but in practice it has been found that two side ponds, economising about half a lockful, are the most advantageous, as the loss by leakage and evaporation from a larger number of side ponds is liable to be greater than the gain.

Two locks placed side by side, with a communication between them which can be opened or closed at pleasure, effect a saving both of water and time as compared with a single lock. For one lock serves as a side pond to the other; and a boat enters one or other of the locks according as the water-level in it is the most suitable, thus preventing or diminishing the loss of time in waiting before entering the lock.

Apparatus at the Aubois Lock. A very ingenious method of storing up a portion of the water discharged from a lock has been applied, by M. de Caligny, at the Aubois lock, on the lateral canal of the Loire. The design is based upon the principle of converting the *vis viva* of running water into a lifting force by suddenly changing the direction of its flow. Thus, for instance, if a current of water is allowed to flow

through a pipe from an upper tank into a tank at a lower level, entering the lower tank by an orifice in its bottom, and if a vertical pipe is suddenly lowered on to the orifice so as to enclose it completely, the water flowing up through the orifice, which is thus prevented from passing into the tank, rises in the pipe, and may be discharged at a higher level than that of the water in the upper tank, till the expenditure of the *vis viva* of the current, and friction, reduce the level to that of the surface of the water in the upper tank. Then, by raising the vertical pipe till the flow is re-established, and again lowering it, another portion of the water in motion is similarly raised. M. de Caligny has adapted this principle to the saving of a certain portion of the water discharged from a higher to a lower level in the process of locking.

A drawing of the whole arrangements at the Aubois lock will be found in M. de Lagrené's treatise[1]; but the modified diagram sketch, given in Plate 3, Fig. 1, taken from M. Debauve's manual[2], shows more clearly the manner in which the contrivance works. The apparatus consists of an aqueduct *a b*, a storage reservoir *c d*, and two movable vertical pipes, *e* and *f*. The aqueduct has two openings at its upper end, one communicating with the reservoir *A* when the pipe *e* is raised, and the other with the reservoir *c d* when the pipe *f* is raised. When the pipes are lowered on to their seats, at the top of each of these openings, communication between the aqueduct and the reservoir *c d* is cut off, and the only means of exit from the upper end of the aqueduct is over the top of the pipes *e* and *f* into the reservoir *A*. The lower end *b* of the aqueduct has its invert at the level of the bottom of the lower pond, and opens into the lower end of the lock-chamber in one of the gate recesses of the lower gates. The reservoir *c d* used to communicate with the lower pond, and was called the discharging culvert, but

[1] Cours de navigation intérieure, de Lagrené, vol. iii, pl. 15.

[2] Manuel de l'Ingénieur des Ponts et Chaussées, Debauve, 19me. Fascicule.

the communication was subsequently closed. The reservoir *A* communicates with the upper pond.

When the lock is to be emptied the pipe *f* is raised, and the water from the lock flows along the aqueduct and enters the storage reservoir *c d*. In a few seconds, as soon as the current is established, the pipe *f* is lowered again on to its seat, and as the water can no longer enter the reservoir *c d* it rises in the pipes *e* and *f*, and some flows over into the reservoir *A* communicating with the upper pond. Directly the discharge has ceased the operation is repeated three times over. By degrees, however, the water in the lock, discharging partly into the reservoir *c d* and partly into the upper pond, becomes so low that the oscillation of the water, on lowering the pipe *f*, is so much reduced as to render the discharge into the upper pond, through the reservoir *A*, insignificant. The pipe *f* is then kept raised, and the water flows freely from the lock into the reservoir *c d*. The rush of water produces a great oscillation, raising finally the water in *c d* to a higher level than that to which it has fallen in the lock. The termination of the oscillating motion is announced by an automatic bell; the pipe *f* is then lowered at once, shutting off the communication between the reservoir *c d* and the lock; and the final emptying of the lock is accomplished through sluices in the gates.

In filling the lock the pipe *f* is first raised, producing a flow of water from the reservoir *c d* to the lock, which causes a great oscillation, and raises the water in the lock to a higher level than that to which it is lowered in the reservoir. The pipe *f* is then lowered at once on to its seat before the level in the two basins becomes equalised. The pipe *e* is then raised, and as soon as the flow between the upper pond and the aqueduct *a b* is established the pipe *e* is lowered on to its seat, and the pipe *f* is raised, which causes the current along the aqueduct to draw some of the water out of the reservoir *c d*, by suction, into the aqueduct and to convey

it into the lock. When this oscillation has ceased, the pipe *f* is lowered on to its seat: and the preceding operation is repeated two or three times, till the water in the reservoir *c d* is at a somewhat lower level than the water in the lock.

The pipe *c* is then kept raised, so as to complete the filling of the lock aided by sluices in the gates. The rush of water through the aqueduct raises the water in the lock to a higher level than the water in the upper pond, causing the upper gates to open spontaneously.

The lock is emptied or filled in five or six minutes. The saving of water, effected by means of this apparatus, in filling the lock is about 40 per cent. of the total volume of water introduced, and the saving in emptying is nearly the same, making a total saving in both operations of nearly 80 per cent., which is increased by utilising the great final oscillations to nearly 90 per cent.

M. Mans introduced lateral aqueducts into the side walls of locks at Herbières and Ath in Belgium for the purpose, originally, of facilitating the entry of large heavily laden boats nearly as wide as the lock-chamber. These boats, acting like a piston, drove the water before them which by its pressure hindered their entrance, and the aqueducts, opening into the far end of the lock-chamber, afforded a side channel for the escape of the water. These aqueducts were subsequently utilised as culverts for working the locks; and in the case of the Herbières lock, M. Mans found that the rush of water through the culvert, in filling the lock, raised the level of the water in the lock above the water-level in the upper pond, and thus, as at Aubois, both caused the upper gates to open spontaneously, and imparted a slight motion to the boat in the lock towards the upper pond. M. de Lagrené suggests that this arrangement might be advantageously extended, so as to be generally applicable, by forming aqueducts, in both side walls of a lock, communicating both with the upper and lower ponds and opening into both

extremities of the lock-chamber. The communication would be made, by means of sluice-gates, between either pond and the far extremity of the lock-chamber, which would occasion sufficient oscillation to raise or lower the level of the lock above or below the level of the pond, and cause the upper or lower gates respectively to open, and help to push out or push in a barge. M. de Lagrené considers that by this means the time occupied in locking might be reduced.

Descriptions of the apparatus, method of working, and the successive modifications at the Aubois lock, have been given in a series of communications by M. de Caligny in the 'Comptes rendus de l'Académie des Sciences;' but unfortunately no illustrations are contained in that publication.

General Remarks. Locks are the ordinary means by which boats are passed from one level to another on rivers and canals. On rivers the fairly continuous and usually abundant supply of water renders locks the best means of connecting the reaches. Simple locking is, however, in reality a very wasteful expenditure of water and force, as is sufficiently manifested by the saving that can be effected merely by the use of side ponds, or still more by the great economy realised at the Aubois lock by the utilisation of the force of the current generated in the process of filling or emptying the lock. It, however, possesses the great merit of simplicity, and even on canals is the best method where the lift between two adjoining ponds can be surmounted by one or at most two locks.

When the supply of water in a canal is small, or becomes inadequate for an increasing traffic, it has to be supplemented, either by increasing the reservoir area, or by reducing the expenditure of water at the locks in one of the ways just described, or by pumping up from the lower to the upper pond a sufficient quantity of water to make good the loss. The choice of methods must depend upon their comparative cost, which varies according to circumstances. The plan

adopted at the Aubois lock economises the expenditure of water to a wonderful degree; but the cost of the apparatus, amounting to £1,600, may hinder the extension of the system, though doubtless successive modifications, as suggested by experience, have raised the cost in this particular instance. Though, however, the actual practical value of the apparatus is not yet established, the experiment is most interesting from a scientific point of view, as affording a fresh illustration how the natural laws of fluid motion may be utilised to a remarkable extent by the proper adaptation of suitable contrivances.

CHAPTER VIII.

WORKS FOR AFFORDING A PASSAGE FROM ONE LEVEL TO ANOTHER (*continued.*)

Inclines: Method of working on the Bude Canal; Barges on Wheels; Cradles; Caissons on Carriages; Method of working the Incline on the Monkland Canal. *Lifts*: Description of the Grand Western Canal Lift; Hydraulic Lift at Anderton and Modifications. General Remarks.

THERE are two other methods besides locks for raising or lowering boats from one level to another—namely, inclines and lifts. These methods are adopted when two adjacent reaches of a canal are situated at considerably different levels, and where it is undesirable to connect them by a flight of locks, either from want of space, scarcity of water, the necessity of rapid transit, or other circumstances.

INCLINES.

Canal inclines are similar to inclines so common in mines and occasionally used upon railways, where very steep gradients are surmounted by drawing up wagons by means of ropes worked by machinery. Canal boats, however, are not adapted for running on rails, so that either special boats have to be provided for the purpose, or a cradle or tank constructed for receiving the boats.

Bude Canal Inclines. Barges with Wheels. The first expedient was adopted on the Bude Canal, where there are two inclines, a short distance from Bude Haven on the Cornish coast, worked by very primitive methods. The barges navigating the canal are small and flat-bottomed,

and provided with little wheels underneath. Two lines of way are laid on the incline, on which the barges run. The barges are drawn up by a rope winding round a drum at the top. The lower and shorter incline is worked by means of a large overshot waterwheel which is set in motion by a stream of water when the drum has to be turned for drawing up a train of barges. At the upper incline there are two deep wells with two huge tubs, suspended by chains exactly fitting into the wells and so arranged and connected that one tub reaches the bottom of one well at the same time as the other comes to the top of the other well. When the train of barges is ready to be pulled up the incline, the tub at the top is filled with water till its weight is sufficient to make it descend, raising the other empty tub to the top of its well, and turning the drum which winds up the rope and draws up the barges. As soon as the barges have reached the summit of the incline the water is emptied out of the tub which has reached the bottom of the well, and the machinery is in readiness for another operation. The descending barges can be let down the incline whilst the others ascend, and assist by their weight in pulling up the others.

Cradles on Wheels. The above plan of employing barges with wheels is however, only suited for a limited traffic, and cradles are usually provided, running on wheels, on to which the barges are floated on reaching the incline, and on which they are conveyed up or down (Plate 3, Fig. 6). This system is employed on a large scale on the Morris Canal in America, on which there are twenty-three inclined planes, with gradients of about 1 in 10, and an average lift of 58 feet, up which boats of thirty tons burden are drawn[1].

Caissons on Carriages. Barges, which are quite strong enough to carry heavy weights when floating in the water, are liable to be strained when raised out of water with their

[1] Sketch of the Civil Engineering of North America by Davis Duncan, p. 206.

load. Accordingly tanks, or caissons, have been designed, which run on wheels on the incline, and in which the barge can be conveyed whilst floating, so that no strain is produced on the barge. This system, for instance, was adopted at two inclines, at Wrantage and Ilminster, on the Chard Canal in Somersetshire. The inclines were double, having two caissons connected by a chain running round a horizontal drum at the top, so that one caisson went up as the other went down, and the motion was imparted by putting more water into the descending caisson.

Monkland Canal Incline. A better known example of this system is the arrangement that was designed by Mr. Leslie, for the Blackhill incline on the Monkland Canal near Glasgow[1]. The incline has a rise of 96 feet, and a gradient of 1 in 10. A double line of way was laid on the incline with a gauge of 7 feet. A carriage with twenty wheels was made for running on each line of way, and so constructed that it could carry a watertight wrought-iron caisson, 70 feet long, $13\frac{1}{3}$ feet wide, and $2\frac{3}{4}$ feet deep, in a horizontal position on the incline (Plate 3, Figs. 4 and 5). The two carriages with their caissons and load of water counterbalance one another, one ascending as the other descends. The carriages are moved by two engines which turn two vertical drums, in opposite directions, round which the wire rope which hauls the load is coiled. The weight of the carriage, boat, and water, is about 80 tons. When a boat is to be taken up the incline one of the caissons is immersed in the lower reach, the lower gate of the caisson is raised and the boat floated in and the gate lowered. The carriage is then drawn up the incline, and on reaching the top the caisson is pressed against the entrance channel of the upper reach, which is closed by a lifting gate so as to form a watertight joint. The gate of the canal and the upper gate of the caisson are then lifted, and the boat is passed into the upper reach. The whole

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xiii, p. 205.

operation only occupies ten minutes, and as one boat can be let into the lower caisson whilst another is being let out of the upper caisson, a boat can be passed up every eight minutes, effecting a saving in time of about twenty to thirty minutes compared with the passage up through the adjacent flight of locks used for descending boats.

Lifts.

The object of perpendicular lifts is the same as that of inclines—namely, to raise or lower canal boats a considerable height at one operation; instead of employing the more tedious arrangement of a flight of locks, which is frequently more costly in construction and involves a larger expenditure of water. As a lift necessitates the raising of the entire load instead of drawing it along, the gearing has to be stronger on a lift than on an incline for the same load. A lift, however, occupies much less space than an incline, and moreover dispenses with the somewhat cumbrous carriage which has to be provided for placing the caisson horizontally on the incline.

Grand Western Canal Lift. The principle upon which the lift on the Grand Western Canal was designed, as described by Mr. J. Green[1], is very simple. Two watertight cradles, or caissons, suspended by chains, were made to ascend and descend alternately in two vertical chambers, resembling a lock-chamber, enclosed by arched masonry walls. The suspending chains, passing over three cast-iron wheels erected over the chambers, were so arranged that one caisson reached the bottom of the one chamber when the other reached the top of the other. Each caisson, being of the same weight and holding the same quantity of water, would have been in equilibrium but for the variation in length of the suspending chains on each side according to the positions of the caissons. The inequality was exactly compensated

[1] Transactions of the Institution of Civil Engineers, vol. ii, p. 185.

by attaching chains to the bottom of each caisson, with the other end resting on the floor of the chamber, equal in weight, per foot of length, to the suspending chains, so that a caisson in rising drew up a continually lengthening chain in proportion as its suspending chain diminished in length, and as the caisson descended the suspended chain coiled up on the floor as the suspending chain lengthened on that side. The ends of the caissons, and the ends of the upper and lower pools of the canal, adjoining the top and bottom of the chamber respectively, were furnished with lifting gates. When a caisson reached the top or bottom of the chamber it was pressed tightly against the corresponding side walls of the canal, between which the canal stop-gate slided, so as to form a watertight joint. The adjoining gates of the caisson and canal were then simultaneously lifted, opening the communication between them.

The caissons, being quite evenly balanced, required for working only sufficient force to overcome their inertia and the friction developed in moving. This was supplied by making the ascending caisson come to rest at such a point that the water-level in it was about two inches lower than the water-level in the upper pool of the canal. The forcing bar pressing the caisson against the sides of the canal kept it fixed at that level, and on raising the gates the water flowed in from the canal raising the water-level in the caisson the two inches. The upper caisson was thus given a preponderating weight of one ton, which, as soon as the caisson was released by the drawing back of the forcing bar, caused the caisson to descend, raising the lower one. The height of the lift, or the difference of level between the two ponds, was 46 feet. The boats conveyed on it were of 8 tons burden, 26 feet long, $6\frac{1}{2}$ feet wide, and drawing $2\frac{1}{4}$ feet of water. The time occupied in passing one boat up and another down the lift was three minutes.

The merits claimed for this lift, as compared with a flight

of locks, were economy in construction, a saving in time of transit, and a small consumption of water. As regards the latter two items, it was estimated that the saving in time amounted to two-thirds of that occupied in passing through a flight of locks, and the saving of water was as much as 92 per cent.

Hydraulic Lift at Anderton. One of the most recent examples of a canal-lift is the one erected at Anderton, in 1875, for affording a communication between the river Weaver and the Trent and Mersey Canal[1], described by Mr. Duer. The difference of level between the water in the canal and in the river is 50 feet 4 inches. A chain of locks was first contemplated, but the space required for such a work, the delay that would be experienced in passing through them, and a scarcity of water in the canal, caused this idea to be abandoned; and it was decided to lift and lower the barges in a trough full of water (Plate 3, Figs. 2 and 3). A basin was formed opening into the Trent and Mersey Canal, and a wrought-iron aqueduct was constructed to form a channel from the basin, over an arm of the river, to the lift pit. A double hydraulic lift was erected on the island, situated between two channels of the river, capable of lifting barges from the level of the river to the aqueduct communicating with the canal. A channel was also cut from the lift pit on the island to the main river channel. The lift consists of two wrought-iron caissons, or troughs, so arranged that one of the troughs whilst lowering barges to the river assists in raising the other trough with its load of barges up to the canal. Each trough is 75 feet long and 15½ feet wide, being long enough to contain the largest barges that can navigate the canal, and wide enough to contain the largest or two of the smaller ordinary barges. The sides of the trough are formed of two wrought-iron girders, 9½ feet deep in the centre and 7½ feet deep at the ends. These girders bear the

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xlv, p. 107.

whole weight of the trough with its load of barges and a depth of five feet of water. The floor of the trough is supported by small longitudinal and cross girders. The trough is closed at each end by a wrought-iron lifting gate. Each trough is supported and moved up or down by a hydraulic ram, 3 feet in diameter, placed under the centre of the trough. The troughs are guided and steadied by guide blocks at each corner, working against guides on the columns at the sides of the lift pit. The aqueduct between the lift pit and the canal is divided longitudinally into two sections, with a lifting gate across each section close to the lift pit, and so arranged at the end adjoining the lift that a watertight joint can be made between the trough and the corresponding section of the aqueduct to which it abuts. Communication is then effected between the aqueduct and the trough by raising the gates.

To enable barges to pass in or out of the trough to the river, it is only necessary to lower the trough so that it may be immersed to a depth of at least five feet in the water at the bottom of the lift pit, and to raise the gate on the river side of the trough.

The rams, which are made of cast-iron, work in cast-iron hydraulic presses situated below the floor of the lift pit. The two troughs are so balanced that, if communication is opened between the two presses when the upper trough contains six inches greater depth of water than the trough at the bottom, the upper trough will descend raising the lower trough. Accordingly, with five feet of water in the top trough, it is only necessary, for working the lift, to reduce the depth of water in the bottom trough to 4 feet 6 inches, which is accomplished by means of self-acting siphons, and to open communication between the presses. The amount of water, therefore, expended in each raising of the lift is only a depth of six inches over the surface of the trough. The equilibrium between the troughs is restored

as soon as the descending trough becomes partially immersed in the water in the lift pit; and the final lift, of about $4\frac{1}{2}$ feet, is performed by closing the communication between the presses and admitting water under pressure, from an accumulator, into the press under the lifted trough, which completes the raising of the trough. The lifting can be accomplished in two and a half minutes; and eight minutes are sufficient for the operation of transferring two barges from the river to the canal, and two others from the canal to the river. The time occupied at Runcorn for a barge to pass through a flight of locks, where the difference in level is the same as at Anderton, is from one hour and a quarter to one hour and a half, showing that the lift effects a great saving of time as well as of water when compared with a flight of locks.

Mr. Duer has since designed a larger lift on the same principle, proposed for the Canal of Neuffossé in France. The troughs in this case are 138 feet long, and $17\frac{3}{4}$ feet wide, the standard size decided to be adopted in future for lock-chambers in France. The vertical height of the lift is 43 feet. Four presses are placed under each trough, arranged in pairs close together. The two inner presses of each pair are permanently connected by pipes, and likewise the two outer ones, so that if one of the presses of either pair fails the corresponding one in the other pair will also cease working. The presses, moreover, of each pair are ordinarily in communication, so that when all is in order the trough would be moved by all four presses; but when the pressure in either pair falls below a certain limit a valve closes and cuts off the communication. This arrangement has been proposed so that, whilst generally affording the advantage of four presses, there may be no overbalancing of the trough, and consequent jamming at the guides, through an unequal working of the presses. This moreover removes the objection made to the Anderton lift, that the safety of each trough depends upon a single press; and also secures the trough

against the jamming that might occur with two presses under each trough, as originally contemplated at Anderton, if one of the presses should fail or stop working.

The principle upon which the greater portion of the lifting is performed at Anderton is the same as that employed on the Grand Western Canal lift, namely, introducing an additional weight of water into the upper of two evenly balanced caissons. This is, however, accomplished at Anderton by removing the required weight of water, amounting to fifteen tons, from the lower caisson. Only one-twelfth of the lift is performed by hydraulic power, which is constantly being stored up by a small engine pumping water into an accumulator.

The expenditure on the Anderton lift would not furnish a fair criterion of the cost of such works, as, besides the high price of iron at the time it was constructed, the foundations had, for local reasons, to be made exceptionally strong, and the accessory works, including the aqueduct, were unusually extensive.

General Remarks. Both inclines and lifts have the advantages over a flight of locks of effecting a considerable economy both in time and expenditure of water. Lifts, moreover, possess a certain superiority over inclines in taking up much less space, and in retaining the boat freely floating in water. The horizontal caisson on the Monkland Canal was intended to realise the latter object; but, owing to the oscillation produced on the water in the caisson during its motion along the incline, the barge was liable to bump against the ends of the caisson, and so the caisson was only partially filled in order that the boat, instead of floating freely, might touch the bottom and be kept still. The boat, accordingly, is only partially supported by the water in its journey along the incline, though sufficiently to prevent the strains produced when a laden boat has to be lifted out of water.

Lifts, however, though worked with a less expenditure of power than inclines, owing to a reduction of frictional resistance, are exposed to the liability of much more serious accidents, if any failure should occur, than carriages running on inclines, as these latter can be easily furnished with brake power to arrest their motion in the event of any fracture occurring to the hauling gear. However, the employment of four presses under each trough of a hydraulic lift, as detailed above, would seem to preclude the possibility of any serious breakdown in a lift of that kind.

A lift appears to be the simpler and better arrangement; but the choice between a lift and an incline depends very much upon questions of expediency and cost. It is a wise maxim in engineering science not to assume that because any one system has proved the best in some particular locality, therefore it is the best system for general adoption, but to weigh carefully the merits of each system as applied to the special case under consideration.

CHAPTER IX.

WEIRS.

Weir Defined. *Overfall Weirs.* Oblique Weir; Angular and Horseshoe Weirs; Construction. Anicuts. *Draw-door Weirs*: Teddington Weir; Draw-doors with Free Rollers. Indian Dams. *Movable Weirs.* The Bear Trap in America and at Laneuville. Frame Weir; Needle Weir; Sliding Panels; Hinged Curtain at Port-Villez; Poses Weir. Shutter Weir; Thénard's Falling Shutter; adapted to Indian Weirs; Mr. Fouracre's Hydraulic Brake; Girard's Hydraulic Shutter; Chanoine's Revolving Shutter. Drum Weirs on the Marne. Segmental Gate Weir at Paris and on the Nile. General Remarks on Weirs.

THE word 'weir' is the modern form of the Anglo-Saxon word *wær* or *wer*, derived from the verb *waran* or *werian*, to hold up; and appears to have signified, in Saxon times, a barrier placed in a river to hold up or enclose the water for catching fish. Even at the present time, wire cages are sometimes fixed across the opening of weirs for catching the fish which come down with the stream; but these cages, by retaining also leaves, sticks, and other rubbish against the interstices between the wires, diminish considerably the available waterway.

A weir may be defined as any sort of barrier placed across a river or canal for stopping, raising, or diverting the water. The equivalent French word *barrage* has a somewhat wider signification; as, besides being used to denote every sort of weir, it is the term employed for reservoir embankments. Weirs are employed for raising the water-level of a river for navigation, for irrigation, or for mills.

Weirs may be conveniently divided into three principal classes:

Overfall Weirs.
Draw-door Weirs.
Movable Weirs.

Overfall Weirs.

An overfall weir is a barrier, wall, or embankment, placed across a river, which affords no passage for the discharge of the stream till the water has risen above the level of its top, or sill. This kind of weir is very efficient in preserving a fixed minimum water-level above it; but it is not suitable for the rapid discharge of flood waters. Overfall weirs are generally placed across the secondary or old channel of a river when the other channel is occupied by a lock. Considering that, in these cases, the whole drainage of the district above, except the small quantity of water which is used in locking, must pass through the secondary channel and over the overfall weir, if no other outlet is provided, it is evident that an overfall weir, raised to the level required for maintaining the proper navigable depth in dry summer weather, diminishes considerably the waterway which existed for the discharge of the river previous to its erection.

Endeavours have been made to mitigate this disadvantage of overfall weirs. Sometimes the sill of the weir is placed below the summer water-level, and is raised in time of drought by placing planks along the top of the sill which are kept in place by upright stakes.

Oblique Weirs. Some weirs erected across the Severn, by Sir W. Cubitt, in 1842[1] (Plate 4, Figs. 1 and 2), were placed obliquely to the stream, in wide places on the river, by which means the length of the weirs, and consequently the capacity for discharge over them, was increased. The Severn has high banks and a rapid fall in the part where the weirs were constructed, so that solid weirs are less objectionable there than they would be in the case of rivers having low banks and a small fall. The river is, in this instance, able to rise a considerable height above the top of the weir without overflowing its banks, and when it does so, the obstruction to the

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. v, p. 340.

discharge presented by the weir is proportionately less. The length of the weirs on the Severn was made such that the section of the waterway over the weir in flood time was equal to the river channel above; but, owing to the less favourable form of the shallower section over the weir, and the impediment occasioned to the flow by the change in form of the channel and in the direction of the current at the weir, the discharge must always be somewhat checked at that part. Also, when the velocity of approach of the current increases, as it does in flood time, the advantage gained in length by the oblique position of the weir is somewhat neutralised: the filaments of the water tend to flow over the sill of the weir in a direction approximating to the axis of the river, instead of at right angles to the weir. The absolute effect of the solid oblique weirs on the flow of the Severn could not, unfortunately, be properly determined, as at the time of their erection the channel of the river was greatly improved, and numerous rocky fords were removed; so that in spite of the obstructions presented by the weirs the discharge of the river in flood time was facilitated, whilst a better navigable depth in dry weather was secured by the deepening of the river and by the weirs.

Angular and Horse-shoe Weirs. As straight weirs placed obliquely across a river, like those on the Severn, tend to divert the main current, and consequently the deepest channel, towards the bank against which the up-stream end of the weir rests, other forms of obliquity are frequently given to overfall weirs. Their sills are sometimes placed in two straight lines, joining in the centre of the river at an angle pointing up stream (Plate 4, Fig. 4); or sometimes a curved form is adopted, the sill being convex on the up-stream side, so that a sort of horse-shoe fall is formed. These forms, whilst increasing the length of the weirs, direct the main stream into a central channel; but the clashing of the currents is liable to produce eddies, and cause undue scour below the centre of

the weir, so that the bottom must be carefully protected at this part.

In France it is very usual for both the lock and weir to be placed side by side in a wide part of the ordinary river channel. In such cases it has been found advantageous, for the purpose of diminishing eddies and back currents near the lock, to put a short length of weir straight across the stream, in the centre of the river, between an oblique weir on the one side and a lock on the other (Plate 4, Fig. 6).

Construction of Overfall Weirs. Overfall weirs are frequently composed of a mound of rubble stone protected on the slopes by pitching (Plate 4, Fig. 2). The up-stream slope is made steep, and the down-stream slope very flat; and the pitching, or a layer of rubble stone, is continued beyond the foot of the down-stream slope to protect the river bed from scour. The top of the weir is surmounted by a sill of timber or stone. A row of sheet piling along the line of the sill, and sometimes also along the toe of the down-stream slope, secures the weir from being undermined by the water (Plate 4, Figs. 2 and 3).

Sometimes the weir is formed by a thick masonry wall, battered on both faces, and with a slight fall up-stream on the top to facilitate the passage of the water over the sill (Plate 4, Fig. 5).

Anicuts. Large overfall weirs have been erected across rivers in India in order to retain and divert the water for irrigation. These weirs, to which the name of anicut has been given in the Madras presidency, keep back the water during the dry season; and in flood time the river flows over the weir. The difference between the low-water level and the flood level is so great, that the weir, whilst high enough to retain a sufficient quantity of water in the dry season, is submerged to a considerable depth during the rainy season, so that it offers less impediment to the flow in flood time than weirs placed across navigable rivers.

In former times the natives used to erect embankments of sand or loose stones, at the close of the rainy season, which served to keep back the water when the river was low, and were washed away by the first flood. These embankments, accordingly, had to be reconstructed every year. Directly, however, these works were entrusted to English engineers, they were made more durable.

Anicuts are now generally constructed of dry rubble, concrete, or rubble stone set in cement, protected on the face by pitching or ashlar masonry set in cement. The up-stream side of the anicut is often built nearly vertical, and the down-stream side has a flat slope, terminated at the base by a stone apron laid on the river bed to prevent scour (Plate 4, Figs. 7 and 8). The foundations are varied according to the nature of the river bed; but generally trenches filled with masonry or concrete are carried some feet below the bed, right across the river, under each toe of the anicut, and sometimes also under the sill, to secure the anicut from being undermined. Walls are built on these foundations, and the intermediate spaces are filled with loose rubble. The Okhla anicut furnishes an example of a work in which no foundations were carried below the bed of the river, but it is very wide in cross section having been considerably enlarged beyond the original design.

Some of these anicuts are very long. For instance the Godavery anicut (Plate 4, Fig. 8), with its sill 12 feet above the river bed, and crossing four separate branches of the river, has a total length of nearly $2\frac{1}{2}$ miles; and the Dehree anicut (Plate 4, Fig. 7), 8 feet high, is $2\frac{1}{3}$ miles long.

Silt and sand brought down by the river tend to accumulate above an anicut, raising the river bed; and sometimes the deposit eventually chokes up the entrance to the irrigation canal, which is usually constructed a short distance above the anicut. Moreover, an anicut, like an ordinary overfall weir, is not suited to discharge a sudden flood or to modify the

levels of the water above it. Sluices, accordingly, are constructed in anicuts to scour away silt and to carry off any excess of water.

Draw-door Weirs.

A draw-door weir consists of a row of piles, frames, or piers, placed generally at regular intervals across a portion of a river, with a series of panels, doors, or planks, to close the spaces between them. These panels, sliding in vertical grooves in the piers, can be raised or lowered from a foot-bridge above, thus opening or closing the weir. Draw-door weirs, accordingly, provide a better discharge in flood time than overfall weirs; they also furnish a means of regulating the level of the water above, and of scouring the channel near the weir.

In mill-streams an overfall weir is usually placed across the bank where the artificial cut to the mill diverges from the old channel; and the natural fall of the stream having been reduced, and the sill of the overfall placed at a high level in order to keep up the water above the mill, draw-door weirs are provided to discharge the surplus water when the mill-gates are closed or in flood time. The doors of these weirs are generally formed of wooden panels sliding in grooves between wooden piles and masonry side walls, and raised by a rack and pinion like the sluices in small lock-gates.

Similar draw-door weirs, on a larger scale, are commonly placed across a portion of a river channel where an overfall weir is situated, so as to regulate and increase the discharge.

Teddington Weir. The last weir on the Thames, at Teddington, designed by Mr. Leach, furnishes perhaps the best example in England of a large composite overfall and draw-door weir placed obliquely across the river. It is divided into four separate bays, and has a total length of 480 feet. Along the three down-stream bays strong wrought-iron frames, formed of plates and angle-irons riveted together, are fixed at regular intervals and carry a foot-bridge on the top (Plate 4, Figs. 9

and 10). The two side bays are overfall weirs. The two central bays, 172 feet 6 inches and 69 feet 9 inches long respectively, are closed by large draw-doors. The longer bay has twenty-three draw-doors, 6 feet high and 7 feet 4 inches wide, formed of plate-iron strengthened with angle-irons; and the other bay has twelve draw-doors. The doors slide in vertical grooves at the sides of the frames. A small tram-road is laid along the foot-bridge, on which a crab runs which lifts the draw-doors by means of a chain.

Free Rollers applied to Draw-doors. In raising a draw-door, a considerable amount of friction is generally experienced at the surfaces of contact along which the two ends of the door slide, especially when there is much pressure of water against the door. This friction has been considerably reduced in some sluice-gates designed by Mr. F. Stoney, by the ingenious contrivance of making each end of the sluice-gate run upon a vertical row of free rollers hung in a recess in each side pier. By this means a sluice-gate at the Pelotas works in Brazil, 20 feet wide, can be raised 10 feet by two men against a pressure of 20 tons. It has been in constant use for seven years without getting out of order, or needing any repairs. Mr. Stoney has made a design for a gate 40 feet in width, and capable of being raised 12 feet, on the same principle.

Further particulars and drawings of this novel contrivance will be found in the Minutes of Proceedings of the Institution of Civil Engineers, vol. lx, where it is described by Mr. Stoney in the course of a discussion on 'Fixed and Movable Weirs.'

Indian Dams. In constructing weirs, for irrigation, across rivers in Northern India bringing down large quantities of sand or silt, it has been found expedient to erect piers in the central portion of the weir with openings between them, about 10 feet wide, which are closed, on the approach of the dry season, by planks lowered horizontally and sliding in grooves

down the sides of the piers. The stone piers rest on a masonry flooring carried across the river, and the weir is built solid for a certain distance from each bank. These partially open weirs are called dams in India. In some instances the openings between the piers in these dams have been made considerably larger, and are closed by gates, turning on horizontal axes at the level of the flooring, which resemble in principle M. Thénard's system of movable weirs, and will be noticed presently. These dams, whilst generally costing less than solid weirs, present less impediment, when open, to the flow of the river, and prevent the accumulation of silt and sand above the weir.

Draw-door weirs, though affording a freer outlet for the discharge of a river than overfall weirs, have their sills placed, in most instances, considerably above the bed of the river, thus obstructing and reducing the waterway. At Teddington weir, for example (Plate 4. Fig. 9), the frames are situated on the top of a rubble mound. This course is adopted for the sake of economy, which is of more importance to those interested in navigation than providing an adequate outlet for the flood waters.

Movable Weirs.

A movable weir is a barrier placed across a river for keeping up the water above it to any desired level, and capable of being so lowered on to the bed of the river, or removed, as to present no obstruction to the waterway in flood time.

Movable weirs were formerly erected on some of the French rivers in order to provide an intermittent navigation, serving in that case the same purpose as the stanches, already described, in producing temporary flashes in the river; but of recent years the necessity for a continuous navigation has been so generally acknowledged, that now locks are almost invariably erected alongside the weirs for the passage of vessels in ordinary states of the river. During floods the

vessels navigating the Seine and other rivers in France pass over the sites of the movable weirs instead of going through the locks, the walls of which are frequently submerged at those periods.

Stanches may be regarded as the first rough type of movable weir. Some falling gates, or shutters, supported by props in an upright position, placed across an overfall on the river Orb in France in the last century, formed the first attempt of adapting movable weirs to overfalls; and the first distinct type of movable weir across a navigable channel was erected in the United States early in the present century.

Five distinct types of movable weirs have been erected abroad. They are as follows:—

1. The Bear Trap.
2. Movable Frame, or Needle Weir.
3. Movable Shutter Weir.
4. Drum Weir.
5. Segmental Gate Weir.

1. *The Bear Trap.*

A movable weir, called a bear trap, was erected, in 1818, on the Lehigh river, Pennsylvania. It was formed by two wooden gates revolving on horizontal axes at the floor level, the up-stream gate pointing down stream, and the down-stream gate pointing up stream. When raised they sloped towards one another, the up-stream gate resting with its upper extremity supported on the top edge of the down-stream gate. This weir is not now in existence; but the type has been reproduced, with improvements, in France, at the weir of Laneuville-au-Pont on the river Marne (Plate 5, Fig. 1). The opening of the weir, in which the gates are placed, is 29½ feet wide. Culverts have been constructed in the side walls of the weir, with openings at the ends into the upper and lower pools, and a side passage from each of the culverts opens into the space under the gates. For closing

the weir, a movable shutter, revolving on a horizontal axis at the floor level and situated above the upper gate, is raised, rising with the stream. This shutter stops the flow of water through the weir, and removes the pressure on the gates. The lower sluice-gates are then closed, and the upper ones are opened. As the water-level in the upper pool above the shutter rises, the water rushes through the side culverts into the space under the gates, gradually raising them; and when the gates have reached their proper height they are fixed in place. The water, continuing to flow from the side culverts, finds its way into the space between the upper gate and the shutter, till the water-level on both sides of the shutter becomes the same, and the shutter can be lowered. For opening the weir, the fastenings of the gates are released, the upper sluice-gates are closed, and the lower ones are opened. The water flows from under the gates, through the side culverts, into the lower pool; and the gates, being no longer supported by the water pressure, fall down and open the weir. The opening of the weir only occupies three minutes.

To close the weir a difference of level of 2 feet is requisite between the water in the upper and lower pools; and the time occupied in closing the weir depends upon the interval which elapses, after the closing of the lower sluice-gates and the raising of the shutter, before the required head of water is obtained. In practice it has been found difficult to gain this head without allowing the lower water to fall too low for navigation; and, consequently, the Laneuville gates are now raised by chains. In order to work this weir properly by water pressure, as originally intended, it would be necessary to provide a reservoir at a suitable level for ensuring the required pressure; but this addition would unduly raise the cost of this type of weir, which is already too expensive, with its two large gates, long side walls, and culverts. It is improbable, therefore, that this type of weir will ever be erected

again, considering the great improvements made in other forms of movable weirs. It, however, possesses a historical interest as being the first well defined type of movable weir erected across a navigable channel, and it is worthy of note as an example of an attempt to raise and lower the weir by the action of the flow of the stream.

2. *Movable Frame Weir.*

Needle Weir. Wooden spars, or needles as they are called in France, were originally used for closing stanches; but the framework of the stanches, against which the needles rested, were not suitable for spanning large openings.

M. Poirée, about fifty years ago, designed a system of movable frames which, whilst serving as a support for the needles when upright, could be lowered on to the bed of the river in flood time, and could be adapted to any length of weir. This invention may be regarded as the first important step in the history of movable weirs. The system consists of a row of light, wrought-iron frames, placed end on to the current at regular intervals apart, connected and fastened together, when standing upright, by movable, horizontal, iron bars, and capable of being lowered flat down across the stream, being hinged to the apron of the weir. Each frame forms a trapezium braced horizontally and diagonally; the frame and braces being formed of bar iron, T irons, channel irons, or angle irons (Plate 5, Fig. 3). The lowest horizontal piece of the frame has iron pins at its extremities, which turn in cast-iron sockets fixed to the apron, and form the hinges of the frame. The horizontal piece at the top of the frame supports a foot-bridge of planks, on which the weir-keeper stands for removing or replacing the needles. The needles, when in place, rest against a sill in the apron at the bottom, and against a horizontal bar connecting the frames at the top. The needles are almost always made square in section, as this form has proved the most convenient in practice, but

oblong and hexagonal sections have been tried. The frames are generally placed at intervals of only 3 or 4 feet, so that they may not be too heavy to be raised or lowered by the weir-keeper.

To open the weir, the needles are first raised one by one and removed, the movable bars connecting the frames are unfastened and withdrawn, and the frames are then gently lowered one after the other by the help of chains, the connecting bars being withdrawn and the foot-bridge taken up, length by length, as the frames are lowered, commencing from one end of the weir.

The weir is reinstated by raising each frame successively by means of the chains attached to them, the bars are fastened on each pair of frames, and lastly the needles are one by one put in place.

The first weir of this kind was erected, in 1834, across the river Yonne; and a detailed description of the third weir constructed on this principle is published in the Annales des Ponts et Chaussées for the year 1839. The frames of this weir were placed $3\frac{1}{4}$ feet apart, 4 feet 7 inches wide at the base, 4 feet 3 inches at the top, and 7 feet high; they were made of $1\frac{1}{2}$ inch square bar-iron. The wooden needles were 8 feet long, $2\frac{3}{4}$ inches by $1\frac{1}{2}$ inches in section, and weighed 13 pounds each. The length of the weir was 230 feet; and $2\frac{1}{3}$ minutes were required for opening a lineal yard of it. In similar weirs, subsequently erected across the Yonne, the distance between each frame was increased to 3 feet 7 inches, and their height was made 7 feet $4\frac{1}{2}$ inches.

Needle weirs have been extensively adopted in France; and all the weirs on the Seine below Paris belong to this type. Three of these are amongst the largest needle weirs hitherto constructed, namely, those at Suresnes, Bezons, and Martot, the last named being at the point of separation between the tidal and non-tidal Seine (Plate 5, Fig. 3). The height of their frames is 11 feet; and the needles are 3 inches

square, and 13 feet long. These weirs are simple, comparatively cheap, and easily worked and repaired. Moreover, by removing a few needles the discharge can be regulated to any extent; or sometimes the simple expedient of pushing out some of the needles at the top away from the frames and keeping them in that position with blocks of wood, enables a sufficient outlet for the discharge to be provided, without the trouble of removing and replacing any of the needles. There is always a certain amount of leakage between the needles, but it rarely exceeds the discharge of the river that must be allowed to pass, if the needles are properly placed and in good condition. Means, however, have been adopted for reducing undue leakage through these weirs, such as closing the interstices with hay, putting a row of covering needles in front, or stretching a tarred canvas curtain along the upper face of the needles.

The limit of height to which needle weirs can be carried has probably been reached at the weirs referred to on the Lower Seine, and at weirs of about the same size across navigable passes on the Belgic Meuse. As the needles rest merely against the sill and the top connecting bar of the frames, their section has to be considerably increased when the height of the frames is raised. Whilst, however, mechanical contrivances have been adopted at some weirs, as for instance on the Meuse, for releasing the needles, they have to be replaced by hand, and therefore cannot be made heavier than the weight one man can conveniently manage.

It has, however, been decided to increase the navigable depth of the Seine between Paris and the sea, which necessitates the erection of some weirs of greater height than any of the previous ones. Accordingly, as the movable frame weir appears to be well suited to that part of the Seine, the engineers in charge of that river have been led to devise some barrier as a substitute for needles in a frame weir.

Sliding Panels on Frame Weir. M. Boulé experimented

on the frames supporting the foot-bridge at Port-à-l'Anglais weir. He employed a series of wooden panels for closing the space between two adjacent frames, sliding in grooves formed in the front of the frames. The panels were lowered one on the top of the other, and raised successively by means of a chain winding on a crab placed on the foot-bridge. As the panels have only to span the opening between two adjoining frames, and can be varied in thickness according to the depth at which they are placed, no excess of timber has to be employed as in the needle weir. Moreover, the number of joints, and consequently the amount of leakage, is reduced; the foot-bridge can be raised above all danger of submergence without adding to the number of panels, and the height to which such a weir could be carried would only be limited to the weight of frame that could be lifted. The design is described in detail, and the results of the experiments at Port-à-l'Anglais are given, in an article by M. Boulé in the Annales des Ponts et Chaussées[1].

Hinged Curtain on Frame Weir. Another method of accomplishing the same object was designed by M. Caméré. The space between each pair of frames is closed by a hinged wooden curtain hanging from the top to the bottom of the weir. This curtain is composed of a number of very narrow boards, joined by hinges, and increasing in thickness in proportion to the depth. The curtain is rolled up, from the bottom, by an endless chain turning round a crab placed on the foot-bridge on the top of the frames. The rolling up or unrolling of the curtain can be stopped at any point, so that the extent to which the weir is opened or closed can be regulated with great nicety. This form of curtain has been adopted for closing the frame weir recently erected at Port-Villez, which is much the largest movable frame weir hitherto constructed, having a height of 18 feet, with frames, each weighing $1\frac{3}{4}$ tons, placed 3 feet $7\frac{1}{4}$ inches apart

[1] Annales des Ponts et Chaussées, 5th series, vol. xi, p. 320.

(Plate 5, Figs. 4 and 5). This weir is the first of a series of works intended to provide a minimum draught of 10 feet between Paris and the sea. Port-Villez weir is situated on the Seine, about two miles above Vernon; it is 656 feet long. There is a lock on the left bank of the river; and the rest of the river channel is divided into three bays by two masonry piers. The large frames are placed across the two bays nearest the lock, which will serve as navigable passes in flood time; and the side bay, adjoining the right bank, has an overfall weir across it, on which a smaller series of frames are placed for closing it in dry weather.

Poses Weir. Another form of weir has been commenced at Poses, below Vernon. This weir bears some resemblance

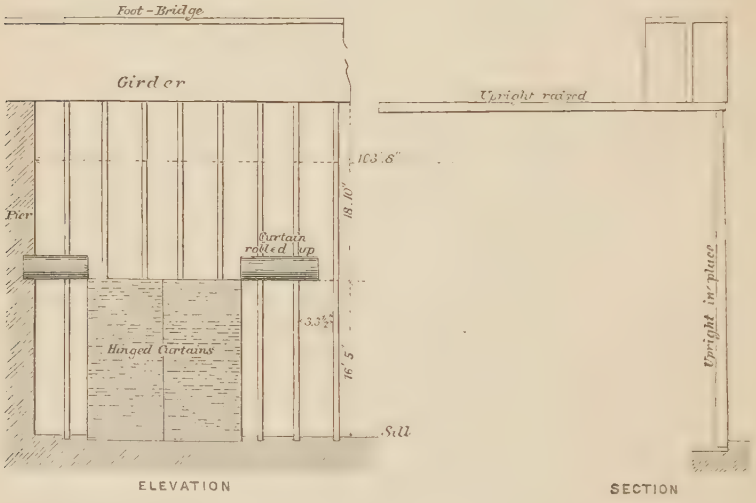


Fig. 16.

to the movable frame weirs in being designed with movable iron uprights, and in the proposed method of closing it by rolling hinged curtains. In other respects, however, the arrangements are totally different from those of M. Poirée's

frames, which have hitherto been invariably adopted in the movable frame weirs.

At Poses weir, piers are to be built in the river, at intervals of about 100 feet, dividing the river into seven openings. Each opening will be spanned by a girder, resting on the top of the piers, at a clear height of 35 feet 3 inches above the sill of the weir. A series of iron uprights will be hinged to the underside of the girder, so as to hang vertically and butt against a projection in the sill when in place, but capable of being raised, by lifting the lower end, so as to assume a horizontal position (Fig. 16). By this arrangement the whole of the framework of the weir can be removed out of the water in flood time, thus securing it from damage and making it easily accessible for repairs. There will be a clear opening of 3 feet $3\frac{1}{2}$ inches between each upright. The girders will support a foot-bridge from which the uprights and curtains will be lowered or raised. This weir will retain 3 feet 3 inches higher head of water above the sill than the weir at Port-Villez.

3. *Movable Shutter Weir.*

Thénard's Shutter Weir. The earliest type of movable shutter weir was erected across an overfall on the river Orb in the last century. It consisted of a gate, or shutter, turning on a horizontal axis at the bottom, supported by a prop when raised against the stream, and falling flat on the apron when the prop was drawn aside. It is evident that considerable difficulty would be experienced in raising such a shutter against a head of water. Accordingly, when M. Thénard erected a somewhat similar weir across three overfalls on the river Isle, between the years 1832 and 1837, he placed a second shutter on the up-stream side of the weir, which, rising with the stream, was retained in an upright position by chains, and stopping the flow of water through the weir enabled the lower shutter to be easily raised and propped

up. Valves were then opened in the upper shutter, and the level of the water being equalised on both sides of it, this shutter could be lowered and secured to the apron, the other shutter remaining upright and forming the actual weir (Plate 5, Figs. 6 and 7). The opening of the weir was readily effected by drawing aside the prop of the lower shutter. The St. Antoine weir, erected in 1843, having seven shutters, 5 feet 7 inches high and 3 feet 11 inches wide, was an extension of the same system. M. Thénard placed a narrow footway along the top of the upper shutters from which the weir-keeper could lift the lower shutters.

Indian Weirs. The system just described was not followed in France after the retirement of M. Thénard, but it has been adopted on a large scale, in recent years, on some irrigation weirs in India. For instance, it has been employed on the Mahanuddee and Cossye rivers, and on the Sone canal, with notable improvements in the latter case[1].

The French weirs only require to be raised when the river is becoming low; but in India the weirs at the head of irrigation canals have to be closed when a sudden fresh in the river threatens to send too great a current of water through the canal.

The act of closing the weir in a rapid current occasions a great strain on the chains which retain the upper shutters in position, as directly these shutters are released from the apron they rise with great force, and frequently the chains or their fastenings are broken.

To remedy this defect Mr. Fouracres has fitted hydraulic brakes to the back of the upper shutters, which, moderating the force with which the shutters are raised by the current, reduce the jar on the chains. This hydraulic brake consists in making the shutter, as it rises, press, by means of a piston, upon a cushion of water, which fills a cylinder when the shutter is down, and is forced gradually, by the motion of

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. lx, p. 43.

the piston along the cylinder as the shutter rises, out of small orifices along the side of the cylinder. The movement of the shutter is made to depend on the motion of the piston along the cylinder. The current forces the shutter upwards, which causes the shutter to draw the piston along the cylinder. The motion, however, of the piston is checked by the retarded efflux of the water through the small orifices. As the piston travels along the cylinder the number of orifices available for the escape of the water is reduced, so that whilst the tension on the piston rod is increased, as the shutter rises, the checking force is also augmented.

In the Mahanuddee weir there are ten bays, each fifty feet across, and each closed by seven pairs of shutters, the back shutters being 9 feet high. There are three sets of movable weirs in the Sone dam, each set being divided into twenty-two openings, these openings being each 20 feet 7 inches wide and closed by one pair of shutters, the back or down-stream shutter being 9 feet 7 inches high.

Hydraulic Shutter Weir. M. Girard erected a movable shutter weir, across an overfall at Brulée Island, on the Yonne, in which he dispensed altogether with the upper shutters of M. Thénard's system, and raised the lower shutters against the stream by hydraulic pressure (Plate 5, Fig. 2). A row of hydraulic presses are placed on the down-stream side of the weir and below its sill. A piston, working in the cylinder of a press, is fastened at its upper end to a cross-head carrying three connecting rods by which it transmits its motion to the shutter, the rods being fastened to an axis placed along the central line of the underside of the shutter. The water pressure is supplied to the presses from an accumulator on the bank; the water is pumped into the accumulator by a turbine, which is turned by the fall of water at the weir. The seven shutters of this weir, each about $11\frac{1}{2}$ feet long and 6 feet high, can be raised in five minutes. The working of this weir has proved quite satisfactory, and

probably the large first cost is the only reason why the system has not been adopted elsewhere.

M. Chanoine's Shutter Weir. M. Chanoine, at a weir which he erected at Conflans-sur-Seine, in 1852, so completely transformed M. Thénard's system as to make it suitable for navigable passes as well as overfalls. The principle of closing the weir by a shutter turning on a horizontal axis was still retained; but the axis, instead of being placed at the bottom, was put a little above the centre of pressure on the down-stream side of the shutter. The axis rests on the top of a wrought-iron tressel standing on and hinged to the apron of the weir (Plate 6, Figs. 1 and 2). When the weir is closed the tressel stands upright, and the shutter, having a slight inclination down stream at the top, abuts at the bottom against a projecting sill on the apron, and is supported in that position by a wrought-iron prop which is connected with the shutter and tressel, and turns, together with the tressel, on the same axis as the shutter. The prop, when supporting the shutter, is inclined at an angle of about 45°, and its lower extremity rests in a cast-iron shoe, from which it can be released by a sideways pull by a bar with projecting teeth, called the tripping bar, which is laid on the apron and worked by a man from the bank. When the prop has been drawn clear of the shoe, it slides down an iron groove on the apron, and the tressel and shutter, being unsupported, are pressed over by the stream and fall, over the prop, flat down on a recessed part of the apron. A form of groove has recently been devised so that a slight movement of the foot of the prop up stream sets it free to slide down the apron; this arrangement dispenses with the necessity of a tripping bar which is difficult to work properly on wide weirs and is liable to get out of order, and a small pull on the shutter up stream suffices to release the prop for lowering the weir.

The shutter is raised, in a horizontal position, by a long

hook from a barge, or from a foot-bridge above the weir by a chain attached to its lower extremity. As soon as the tressel has been raised, and the prop is in the shoe, the lower extremity of the shutter is released, and it closes, either under the pressure of the water alone, or, if necessary, by the aid of a push at the bottom or by a pull from a chain attached to the top.

This type of weir is employed both across navigable passes and on the top of overfalls. Usually the navigable pass, with its sill close to the bottom of the river, is made of such a width as is necessary to meet the requirements of navigation and to provide a sufficient outlet for the river in the event of summer floods. The remainder of the river channel, except the space occupied by a lock, is closed by a weir, with its sill placed at a higher level, on the top of an overfall, for the sake of economy (Plate 6, Fig. 2). The axis of rotation of the shutters in an overfall shutter weir is so placed that, when the water rises a certain height above the weir, the pressure on the upper portion of the shutter overcomes the pressure on the lower portion, and the shutter turns on its axis, opening the weir, till the lowering of the water reverses the balance of pressure and the weir closes again. The overfall weir is, accordingly, employed to regulate the water-level of the river; whilst the axis of the shutters of the navigable pass is placed high enough above the centre of pressure to prevent their opening of their own accord. Though the overfall weirs were designed to be self-acting, it has been found expedient to place a foot-bridge, on movable frames, above the weir, so as to regulate with more precision, by means of chains, the extent to which the weir is to be opened. The overfall shutters are not generally lowered on to the apron except in winter.

Small shutters, called butterfly valves, are sometimes placed in the upper panels of the large shutters across a navigable pass, which turn on horizontal axes so situated that the

valves open when the river rises above a certain height, and thus serve to regulate small variations in the level of the upper pool.

It has been found that a foot-bridge so much facilitates the management of the shutters, that several navigation passes on the Marne have been provided with one; but this addition increases considerably the cost of a weir.

The largest shutter weir hitherto constructed is placed across a navigable pass at Port-à-l'Anglais weir on the Seine, a short distance above Paris (Plate 6, Fig. 1). It was erected, in 1869, to supply the place of the lock during repairs. The shutters are able to retain a height of $13\frac{1}{2}$ feet of water above the sill of the weir; each shutter is $3\frac{1}{4}$ feet wide. They are raised or lowered from a foot-bridge supported on movable frames 15 feet 9 inches high.

Movable shutter weirs of the Chanoine type are now being erected across the Great Kanawha river in the United States. They are used for closing both the overfalls and navigable passes; and foot-bridges, on movable frames, have been provided from which to work the weirs, as in the most recent French examples.

4. *Drum Weir.*

The drum weir was invented by M. Desfontaines, and introduced by him on the overfall weirs of the river Marne. It consists of an upper and under iron paddle, capable of making a quarter of a revolution round a horizontal axis between them. The upper paddle forms the weir, which it closes when upright; and the under one, which in order to work easily should be made slightly larger than the other, revolves in a closed recess below the sill of the weir. This recess has the form of a quarter of a cylinder, lying horizontally along the weir, which is the cause of the name drum being given to this type of weir (Plate 6, Fig. 3). The upper paddle is straight; but the under paddle is curved in such a

manner, near its junction with the axis, that a space is left between its upper face and the top of the drum, when both paddles are horizontal, through which water can be admitted so as to press upon its upper face. A similar space is left, by a prolongation of the drum, between the down-stream face of the under paddle and the vertical wall of the drum when both paddles are vertical.

The weir is closed by raising a sluice-gate, in the abutment at the end of the weir, which opens communication between the upper spaces in the drums and the upper pool; the water from the upper pool presses on the upper faces of the under paddles, and, overcoming the pressure of the water on the upper paddles, closes the weir.

The weir is opened by lowering the sluice-gate, so as to remove the water pressure from the upper face of the under paddles, which allows the current to lower the upper paddles and open the weir.

The arrangement in the abutment for working the weir actually consists of two sluice-gates moved by a see-saw arm, so that one goes up as the other goes down; and by this means communication between the upper and lower pools and the drum, and consequently the pressure on either side of the under paddle, can be regulated with extreme nicety. Accordingly the weir-keeper, by turning a handle on the abutment which moves the see-saw arm, is able to open or close the weir more or less, to any extent, with perfect ease. The weir at Joinville, one of the largest and most recent examples of this type of weir, was erected across the Marne in 1867. It is closed by forty-two paddles, 3 feet 7 inches high and 4 feet 8 inches wide. It can be completely opened or closed in three or four minutes by one man; it has worked perfectly, without requiring any repairs since its erection beyond an occasional coating of tar.

Unfortunately the drum weir is only suitable for overfalls, as the depth to which the foundations have to be carried

below the sill, to provide for the under paddle and drum, precludes much height being given to the weir. Also it compares unfavourably, in first cost of construction, with needle or shutter weirs. Accordingly, in spite of the ease and precision with which the drum weir can be worked, it is unlikely to be ever extensively adopted.

5. *Segmental Gate Weir.*

A peculiar form of weir may be seen across a portion of the Seine in about the centre of Paris. This weir, forming a part of the 'barrage de la Monnaie,' has three openings of 28 feet 9 inches separated by masonry piers. These openings are each closed by a kind of wrought-iron cellular gate made in the form of a segment of a cylinder. It revolves on a horizontal axis, round pivots fixed in each pier, with which it is connected, at each side, by six radiating iron rods (Plate 6, Figs. 4, 5 and 6). The gates are counterbalanced by weights rising or falling in a hollow in the piers. They are by this means easily turned through a small arc by chains worked from the piers, closing or opening the weir according as they are raised or lowered. They were designed by M. Poirée, in 1853, with the special object of being out of sight when lowered, and of offering no obstacle to the floating away of rubbish coming down the river, as it was considered that an ordinary frame weir would detain rubbish and be unsightly in the centre of the city.

The only other example of this type of weir is to be found on the Nile at the Rosetta barrage. This weir, with sixty-one openings, each 19 feet high and 16 feet 4 inches wide, is closed by segmental gates similar to those at La Monnaie weir, from which it was doubtless copied. The gates, however, in this instance appear to have been badly designed and executed, and they are worked with difficulty.

General remarks on Weirs. Nothing perhaps exemplifies

more clearly the different amount of attention paid in England and France to the navigation of the upper portions of rivers than the history of recent improvements in weirs. In England few new weirs have been erected of late years, and hardly any novelties in their construction have been introduced; whereas in France the form of weirs has undergone an entire transformation within the last fifty years, in which period all the types of movable weirs have been designed, constructed, constantly extended, and improved. It indeed suffices to take a walk in the environs of Paris, and to make a day's trip to the weirs of Port-Villez and Poses on the Lower Seine, to see what an important part movable weirs occupy in that country as regards river navigation. Though, however, France has taken the lead in this matter, Belgium is following her example; and the value of movable weirs is beginning to be fully recognised in India and the United States.

The two causes to which the absence of progress in this respect in England may be attributed, are, the smaller size of the upper rivers, and the absorption of river traffic by railways. The traffic on rivers is, indeed, so low in England as not to justify much expenditure on improvements; but movable weirs are valuable for another purpose, which will be referred to later on when the subject of floods is considered.

Solid overfall weirs possess the advantages of economy, small trouble in maintenance, and no expense in working; they, moreover, do not very materially affect the discharge when a river having high banks rises a considerable height in flood time.

Draw-door weirs occupy a sort of intermediate position between solid and movable weirs; they are cheaper than movable weirs, and somewhat easier to manage; and they afford a freer flow than solid weirs, admitting a regulation of the discharge, and consequently of the levels, of a river.

Only three types of movable weirs are likely to remain in use; these are, the movable frame weir, the shutter weir, and the drum weir; and the two first only will probably be generally adopted.

The drum weir is superior to the other two in facility of working and ease of adjustment; but, unfortunately, it has two important defects; first, a large cost in construction, which however is somewhat compensated for by economy in subsequent maintenance; and, second, the deep foundations below the sill rendered necessary by the drum. This latter defect prevents its being used for navigable passes; and the former has probably been the cause of its having been restricted to the river Marne, where it was introduced by its inventor. As an ingenious hydraulic contrivance it far surpasses the others; but it serves to illustrate how an excellent apparatus, in theory, may not prove equally satisfactory in practice, not from any faultiness in design or defect in working but owing to subsidiary considerations.

Shutter weirs of the Chanoine type have been largely used in France, and are being introduced with success on the large rivers of North America; whilst the Thénard system of falling shutters, in a modified and enlarged form, is preferred in India. Shutter weirs are suitable both for overfalls and navigable passes, and, theoretically, they should enable the current of a river to regulate the discharge automatically: there is, however, a difficulty in accomplishing this with sufficient precision, and it has been found expedient to add a movable frame foot-bridge above the weir, which notably increases the cost. The maintenance of the shutters, which are liable to be injured in falling on the apron, is rather troublesome and costly; but this is remedied by the help of the foot-bridge, as the shutters can then be lowered gently by chains from the bridge. The necessity of using a tripping bar, entailing delays and fractures, has been obviated by the adoption of the double-grooved shoes employed on the Mula-

tière weir on the Saône: also the adoption of iron in place of wood for the shutters will notably increase their durability. These improvements render the Chanoine shutter weir perfectly manageable and easy of maintenance; and the success of the system is sufficiently indicated by its constant extension. The only objection that can be urged against the improved shutter weir is its cost. Originally the shutter weir with its tressel and prop formed the entire weir; but since the addition of a movable frame foot-bridge the conditions have altered, and a comparison is naturally suggested between the shutter weir and the movable frame weir, and the question arises whether a cheaper barrier than shutters should not be provided to act in conjunction with movable frames.

In the movable frame weir the frames serve the double purpose of forming the support for the weir and also for the foot-bridge, whilst in the shutter weir they only support the foot-bridge. The needle weir evidently has limits to its increase in height, owing to the increased weight of the needles[1]; but the sliding panels, and the hinged curtains, are applicable to any height, and are unquestionably much cheaper barriers for closing a frame weir than shutters. Though therefore shutter weirs are, at present, in many cases preferred to movable frame weirs, it seems likely, if M. Boulé's and M. Caméré's systems are found after longer experience to work well and to be sufficiently watertight, that the movable frame weir, with some such movable barrier, will eventually prove the simplest and cheapest form of movable weir.

[1] A description is given in the 'Annales des Ponts et Chaussées,' September 1881, of a simple and ingenious contrivance which will facilitate the working of needle weirs. Each needle is provided with an iron hook which encircles the upper front bar connecting the frames. The needle can therefore rotate on the bar as on an axis. Accordingly the weir-keeper in closing the weir, instead of lifting each needle, has only to push the needle across the foot-bridge till it hooks on to the bar, and then by lifting the handle of the needle the other end is lowered, and being immersed in the current, is driven into place against the sill.

CHAPTER X.

VARIOUS WORKS ON RIVERS AND CANALS.

Waste Weirs. Stop-Gates. *Reservoir Dams*: Earthwork Dams; Masonry Dams; Furens Dam; Theoretical Forms; Ancient Masonry Dams. *Quay Walls*: Theory and Practice; Failures due to Foundations; Remedies. *Movable Bridges*: Swing-Bridges; Bascule Bridges; Traversing Bridges; Lift-Bridges; Pontoon Bridges.

Waste Weirs. When a canal is fed by a river or water-courses it is necessary to provide some means of regulating the supply of water, otherwise an over abundant supply in flood time might cause the water to overtop the banks, both stopping the traffic and injuring the banks and the adjacent land. Accordingly overfall waste weirs are provided, at suitable places, which discharge the water into water-courses, or into cuts leading to adjacent streams, when it rises above a certain level. The level is fixed by the height given to the sill of the weir, and the discharge of water by its length.

Stop-Gates. As canals are artificial channels containing sometimes large volumes of water above the ordinary level of the land, it is important to take precautions against the extensive flooding of the adjacent land, and the laying dry of a long reach of a canal, which the sudden failure of a bank might entail. Long canal reaches on embankments are consequently divided into several sections by stop-gates, which either consist of a pair of gates, similar to lock-gates, or of a series of planks let down between grooves in vertical walls on each side of the canal, the walls being either con-

structed for the purpose, or consisting of the piers of bridges over the canal in which grooves have been made. This division of the canal into comparatively short sections is, moreover, also valuable in the event of any repairs being needed, as thereby only a portion of the water in the reach has to be drawn off.

Reservoir Dams.

Mention has already been made of the method of providing a supply of water for canals by placing reservoir dams across the valleys of rivers or watercourses, so as to accumulate their discharge in an artificial reservoir, or lake, bounded by the slopes of the river valley and the dam The dam is provided with an overfall weir, for letting off the surplus discharge into the old channel below after the reservoir has been filled: with an outlet culvert for conveying the water from the reservoir to the channel supplying the canal; also generally with a discharge culvert for lowering or emptying the reservoir; and sometimes collecting channels are made in the valley above for bringing the supply to the reservoir.

Earthwork Dams. If the foundation consists of rock the dam may be constructed of masonry, but with any other foundation it is generally advisable to form an earthwork dam. An earthwork dam consists of an embankment with slopes on both sides, the outer slope being formed to any angle at which the material composing it will stand, and the inner slope very flat, and pitched to protect it from the wash of the water in the reservoir. The central wall, or trench, of puddle secures the watertightness of the dam; and sometimes the inner slope is coated with a layer of watertight material to preserve the interior of the embankment from the action of the water. The junction between the bottom of the dam and the foundation is made as close as possible by removing all loose soil, and sometimes by carrying longitudinal trenches below the general level of the bottom of the dam. The

greatest care has to be taken in bringing up the dam in thin horizontal layers well punned. Some clays are so liable to swell and slip, when exposed to the weather and the action of water, that great trouble has been sometimes experienced in retaining the slopes of embankments made of clay. Thus, for instance, the dam of the Cercey reservoir on the Bourgogne canal, composed of clay of the lias formation, 39 feet high and with slopes of 2·4 to 1 and 2 to 1, has been on several occasions injured by slips. The embankment has been always repaired by removing the displaced material, building masonry walls at intervals of about 30 feet on the site of the slip, at right angles to the line of the dam, and replacing the material in the spaces between the walls, which was finally covered with pitching. The dam of the Torcy reservoir on the Canal du Centre also suffered from slips, owing to too large a proportion of clay having been used in the embankment and the punning having been insufficient. These slips were repaired in a very similar manner to those on the Cercey dam[1]. The object aimed at in these repairs was to separate and support the masses of clay. It is evident, from these examples, that it is unwise to construct an earthen reservoir dam entirely of clay; and it should either consist of a central puddle trench with less close material on the outside, or of clay with a certain proportion of sand. M. Comoy thinks the proportion of clay in a homogeneous dam should not exceed 30 per cent.

Earthwork dams are the best for small heights; but some French writers consider that, where the foundation consists of a compact stratum, masonry should be adopted for dams exceeding 40 feet in height. Earthwork embankments, however, are almost universally employed in this country, the highest being the dam of the Entwistle reservoir, of the Bolton water works, retaining a depth of water of 120 feet. In France, also, earthen dams exceeding 40 feet in height

[1] Annales des Ponts et Chaussées, 5th series, vol. x. pp. 27 and 30.

have been constructed, as for instance the Montaubry dam (Plate 7, Fig. 1), on the Canal du Centre, which has a height of 54 feet.

Masonry Dams. The highest dams, however, have been constructed of masonry. Thus the Furens dam, across the valley d'Enfer, is 170 feet high (Plate 7, Fig. 2). This dam, which is 164 feet wide at the base, diminishing to $18\frac{3}{4}$ feet at the top, possesses a special interest, as its section coincides very nearly with the form that theory would assign to such structures exposed to fluid pressures[1] (Plate 7, Fig. 3). The resultant pressures on the masonry, when the reservoir is full and empty, are shown in dotted lines; and the dam has to be so designed that these pressures may fall well within the base, and not occasion at any point a greater pressure than the masonry is calculated to sustain without injury. The Furens dam has been designed so that the maximum pressure on the masonry shall in no case exceed $85\frac{1}{3}$ lbs. on the square inch; and in the theoretical type of dam the same limit has been assumed. The Furens dam evidently possesses ample stability, but it was the first dam erected approaching the theoretical type; and it is of the utmost importance that the security of a dam of such magnitude should be fully ensured, when, not only the adjacent country, but towns and their inhabitants would be imperilled by any failure. A more recent dam of a similar type at the Ban reservoir, 138 feet high, has had the maximum limit of pressure on the masonry increased to $113\frac{3}{4}$ lbs. on the square inch. It is clear that by improving the quality of the mortar, as for instance by employing cement mortar, it might be possible to increase this limiting pressure still further; and M. Graëff has given 200 lbs. on the square inch as the probable extreme limit in this direction, and under these conditions the theoretical type would be modified in form as shown in Plate 7, Fig. 4. This latter pressure has indeed

[1] Annales des Ponts et Chaussées, 4th series, vol. xii. pp. 184 and 212.

been imposed in the case of the Almanza dam in Spain, which was erected in the sixteenth century and is still in a sound condition (Plate 7, Fig. 5). The choice of section may be said to lie practically between the two theoretical sections given, and it must depend upon the strength of the materials available; whilst a harder material set in cement mortar may prove the most economical, owing to the reduction that can be effected in the section.

Other Spanish dams have not been so boldly designed as that of Almanza, as will be perceived by reference to the section of the Alicante dam, 134½ feet high, and nearly three centuries old, and of the Puentès dam, 164 feet high (Plate 7, Figs. 6 and 7). A comparison between these and the Furens dam, indicates what economy a due regard for theoretical considerations can effect, whilst actually reducing the weight on the foundations.

Quay Walls.

A quay wall is constructed along a river bank, either for the purposes of trade, as at Antwerp, in which case it serves practically as a tidal dock wall, or for the purpose of reclaiming the foreshore, and rectifying and improving the river channel, as at London and Paris. Quay walls have to resist a lateral pressure of earthwork at the back tending to overturn, crush, or force them forward. This pressure, however, instead of being a uniform and easily calculated fluid pressure, as in the case of reservoir dams, varies greatly according to the material at the back of the wall. A quay wall, like a dock wall or retaining wall, is erected for the purpose of enabling the surface of the ground at the back of the wall to be carried up level with the adjacent land. In the absence of any wall the ground would have to be dressed to a certain slope which would depend on the quality of the material. Thus, whilst chalk and rock can stand at about a ¼ to 1 slope, some silty soils require a slope of 3 to 1, or even more.

Moreover, some clay soils, whilst apparently firm and able to stand at a steep slope when first opened out, tend to disintegrate and to assume a pasty condition when exposed to the weather and the action of water. Every sort of material has its own natural slope which is liable to vary according to the size of the separate particles, the consistency of the material, and its condition.

The general theory commonly employed for calculating the stability of walls has been, that, supposing a wall, *A B* (Fig. 17), to be backed by a material whose natural slope is *B C*, the lateral pressure of the earth against the back of the wall is equivalent to the weight of the quantity of earth contained between the vertical *AB*, and a line *BD*, bisecting the angle *A B C*. In an interesting paper on this subject, however, recently read at the Institution of Civil Engineers[1], Mr. Baker shows that this assumption is not borne out by the experiments, somewhat few in number, made at various times to ascertain the actual pressure with different materials. He comes to the conclusion that the real pressure is only about one half what has been generally assumed; but as he would propose to introduce a factor of safety of 2, for which no allowance appears to have been made by the old theory, the final result would be practically the same. But whatever may be the results of further experiments, which are much needed before the subject can be established on a sound theoretical basis, it is quite certain that, in practice, these walls are almost invariably made amply strong, and that the failures which have occurred may in nearly every instance be attributed to faulty foundations.

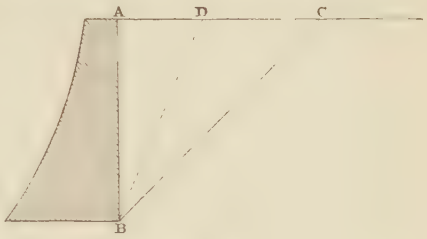


Fig. 17.

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. lxv, p. 140.

A few examples of quay and dock walls are given in Plate 7, Figs. 8 to 15, for the purpose of indicating the varieties of form, and methods of construction that have been adopted.

Under favourable conditions, walls having an average thickness of one-fourth of their height, and having a batter of one or two inches to the foot on the face, have been found to stand well. Mr. Baker states that, in his own practice, he has constructed retaining walls, in average ground, having a thickness of one-third of the height from the top of the footings, with very satisfactory results.

The two kinds of failures that are liable to occur with faulty foundations are: (1) The settlement or overturning of the wall, owing to the inability of the foundations to support the weight of the wall or the pressure at its outer edge; (2) The sliding forward of the wall, owing to the pressure at the back overcoming the frictional resistance under the wall. In the first case, the foundations should be consolidated by piles, or the weight distributed over a broad base, and the foundations of the wall carried well forward in front of the face of the wall. The latter contingency must be provided against by securing the toe of the wall, either by driving sheet piling in front of it, or by carrying the foundations down to a lower level than usual, so as to have a good mass of solid ground in front of the base of the wall to counteract its tendency to slide. This is preferable to the plan sometimes advocated of merely increasing the size and consequently the weight of the wall; for, though a heavier wall increases the frictional resistance at the base, it is better to apply additional material where it is actually required, thereby increasing its efficiency, rather than to distribute a larger amount over a wall already amply strong enough to sustain the pressure at the back.

When water is liable to accumulate at the back of the walls during construction, it is advisable to employ, if possible,

backing suitable to promote drainage; and also to bring small pipes through the walls near their base, at regular intervals apart, to enable the water to escape, and prevent its rising at the back and adding thereby the hydrostatic pressure of the water to the normal pressure of the backing, and also in order that it may not gradually ooze through the wall and interfere with the setting of the mortar. These holes should be carefully stopped up just before the water is admitted against the face of the wall.

There is a general tendency to make walls broader at the top and narrower at the base than theory would indicate as correct; this is due to the inconvenience a very curved batter on the face causes to ships lying alongside, and the additional expenses wide foundations entail; but a wall more nearly approaching the theoretical section of a masonry dam would enable a more stable wall to be constructed with less material. The Sheerness quay wall (Plate 7, Fig. 15) has an excessive thickness, but it possesses a general form of greater stability than most quay and dock walls.

Movable Bridges.

It sometimes happens that the levels of roads or railways, crossing ship-canals or tidal rivers, cannot conveniently be raised to a height sufficient to afford a proper headway under the bridge for masted vessels. In such cases it is necessary to construct a bridge which can be moved out of the way for vessels to pass. This type of bridge is termed a movable bridge. The various forms of movable bridges are well described, by Mr. James Price, in a paper read before the Institution of Civil Engineers in 1879[1].

Swing-Bridges. The most convenient and most commonly adopted form of movable bridge is where the bridge turns horizontally on a pivot, placed approximately under its

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. lvii, p. 1.

centre of gravity, enabling the bridge to be either turned across the stream so as to close the opening between the piers, or to be placed parallel to the stream on the abutment on the shore, or on a pier in the river, and thus leave the channel open. This form of bridge is called a swing-bridge.

In order to balance a swing-bridge spanning a single opening it is necessary to make a prolongation of the bridge on the shore side of the pivot placed on the abutment; this prolongation is called the tail-end. The balance is accomplished in the simplest manner, and with the least weight of metal, when the tail-end is made symmetrical to the swing portion (Plate 8, Fig. 1); but frequently this arrangement would take up too much quay space. The tail-end is, accordingly, usually made shorter than the other, and the deficiency in weight is made up by placing cast-iron kentledge on it (Plate 8, Fig. 2). This plan, however, possesses the disadvantage of increasing the total weight of the bridge, and, consequently, the friction on the pivot, and the amount of force required to turn the bridge. This is especially the case when the tail-end is made very short, as then a large amount of extra weight has to be added to allow for the diminished leverage. This defect is very well illustrated in the case of the Hull South Bridge, whose swing portion is 121 feet in length, whilst the tail-end being only 49 feet long requires a counterpoise of 500 tons, whereas the weight of the bridge is only 300 tons. Also, when the two portions are very uneven, and the webs of the girders are solid, the wind exerts a considerable excess of pressure on the swing portion, which is frequently intensified by the tail-end being more or less sheltered, as at Hull, whilst the swing portion is exposed to the whole force of the wind. This inconvenience is partially remedied by substituting lattice for plate girders, which can be done with advantage in large bridges, though inconvenient and expensive for small bridges owing to the difficulty and cost of the connections of the lattice bars to the flanges.

The most economical form of swing-bridge is where the space to be spanned can be divided into two equal openings; in this case the pier on which the bridge turns is placed in the centre of the stream, the two portions of the bridge, on each side, are made symmetrical and balance one another, and no portion of the bridge is wasted in acting as a counterpoise (Plate 8, Fig. 3). Another form of swing-bridge, which used formerly to be frequently adopted for small spans, is shown on Plate 8, Fig. 4. It consists of two symmetrical segments of cast-iron, meeting, when the bridge is closed, in the centre of the span, each turning on one of the abutments and balanced by a tail-end. The bridge, when closed, forms an arch; and by locking together the two extremities at the crown, and letting down hinged struts, as shown in the illustration, it is possible to render the arch more or less available for assisting in supporting the loads passing over the bridge. Wrought-iron is now generally adopted for these bridges; and the finest instance of a wrought-iron swing-bridge of this type is the bridge at Brest, over the river Penfeld, which affords a clear opening of 350 feet between the piers and has a span of 385 feet between the centres of the supports (Plate 8, Fig. 5). M. Gaudard, however, in a valuable paper[1] treating of the strains to which the various types of swing-bridges are subjected, has pointed out that the connection of the two portions at the centre of the span of the Brest bridge is not perfect enough, nor the rise sufficient, nor proper springings provided, to enable the bridge to be treated as an arch; but the fastening of the extremities of the tail-ends to the masonry, when the bridge is closed, assists in bearing a portion of the strains which tend to lift the tail-ends when the long bracket arms are loaded.

Swing-bridges are turned either on a ring of rollers, or on a pivot, or on both combined, or on a water centre on which they are supported by hydraulic power. Frequently rollers

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xlvii, p. 221.

are placed near the extremity of the tail-end of the bridge, and then the tail-end being made slightly the heaviest there is no danger of the other end being overbalanced, and the bridge bears upon the tail-end rollers which guide its motion.

Facility of motion is of great importance in these bridges, as the convenience of navigation across, and of traffic over the bridge, is dependent upon this. The time, however, in which the operation is performed varies considerably: thus the bridge at Athlone, over the Shannon, 130 tons in weight, occupies thirty-five minutes in opening by manual labour; whereas the opening of the Marseilles bridge, weighing 684 tons, is accomplished in three minutes by hydraulic machinery. This great difference in time must not be wholly attributed to the advantages hydraulic power possesses over manual labour, but is partly due to the design; for the Brest bridge, of which each half weighs 350 tons, is moved, like the Athlone bridge, by manual labour, but only occupies a quarter of an hour in opening. The great advantage, however, gained by the employment of hydraulic machinery for moving heavy weights easily and rapidly, is well illustrated by the case of the Marseilles bridge, where one man performs the operation in any weather. The designer of this bridge, M. Barret, is indeed so well assured, from his own experience, of the adaptability of hydraulic power to such purposes, that he considers that a swing-bridge weighing 2500 tons could be constructed on similar principles, with slight modifications, which could be opened in an equally short period of time.

Another type of swing-bridge has been erected at Dublin by Mr. James Price, to which he has given the name of floating swing-bridge. The bridge is supported on a buoy floating in a well formed in one of the abutments, and the bridge is moved round by turning the buoy (Plate 8, Fig. 7). The buoy is made to rest lightly upon a small pivot fixed at the bottom of the well, so that the buoy is always submerged, and thus its position is not affected by alterations of the water-

level in the well. The advantage of this system consists in the small amount of weight thrown upon the bridge foundation.

The substitution of steel for wrought-iron, which has proved very useful in reducing the weights in the case of some large bridges, as for instance the St. Louis Bridge over the Mississippi, would be specially advantageous in the case of movable bridges; for here a double reduction would be effected, as, besides reducing the weight of the portion spanning the opening, the weight of the counterbalancing arm would be equally reduced. Even with the somewhat low limit of strain of 6½ tons per square inch, allowed for steel by the Board of Trade, the reduction in the weight of the girders would be one-fifth, an amount of considerable importance when it is borne in mind that this weight has to be moved each time that the bridge is turned.

Bascule Bridges. These bridges in opening are raised at the outer extremity, revolving on a horizontal hinge, or axis, placed on the abutment. The ancient drawbridges of fortresses are specimens of this class of bridge. When the opening to be spanned is not very small, the bridge is composed of two flaps revolving on an axis on each abutment and meeting together in the centre of the opening.

In the regular bascule bridge a tail-end is constructed for balancing the portion spanning the opening, and it is necessary that a pit should be provided into which the tail-end can sink when the bridge is raised. Unfortunately, if the water-level is near the surface, water finds its way into the pit, which is detrimental to the maintenance of the tail-end, and diminishes its effective weight as a counterpoise to the other portion.

In Holland, accordingly, large overhead beams, resting upon wooden supports, are used to counterpoise the wooden drawbridges and raise them by means of connecting chains. Numerous examples of this type of bridge may be seen at Amsterdam, where they are commonly adopted for providing a passage over the intricate network of canals which extends

over every part of the city. A simpler form of wooden bascule bridge is usually employed in the country districts of Holland for carrying the roads over canals. Two long heavy wooden beams, with thick butt ends, are fastened to each side of the bridge at its axis, and serve as a tail-end in counterpoising the bridge. The beams are arranged to project from the bank with their ends in the air at such an angle that when lowered to a horizontal position the bridge is raised. As these beams nearly counterbalance the bridge, a slight downward pull of the chains hanging from their ends suffices to raise the bridge which, as soon as the chains are released, returns to its bearings. These wooden drawbridges are only suitable for small spans; and the increasing difficulty of obtaining large enough beams, and the cost of repairs, is gradually leading to the substitution of iron.

A good instance of an iron bascule bridge is the Selby bridge over the river Ouse (Plate 8, Fig. 6). The bridge has girders of an arched form and abutting against the masonry of the piers, which renders it very firm. It has a span of 45 feet, and can be opened in $1\frac{1}{2}$ minutes. A bridge erected at Copenhagen a few years ago is the largest bascule bridge hitherto erected; it spans an opening of $56\frac{2}{3}$ feet. As the tail-end of this bridge is very short, it bears a counterpoise of 57 tons.

Bascule bridges are not suitable for large spans; and objections have been raised against their employment, namely, that they are liable to catch the rigging of passing vessels, and that they expose a large surface to the wind. A bascule bridge, however, erected at Bristol, 42 feet wide and rising up 46 feet when opened, is stated to have worked satisfactorily in spite of the large surface exposed, and it is opened by steam power in the very short space of half a minute.

Traversing Bridges. Sometimes the narrowness of the abutment of a movable bridge, or other circumstances, preclude the adoption of a swing-bridge. Under such conditions,

if the use of a bascule bridge is not advisable, a traversing bridge is employed. This type of bridge rolls forwards and backwards, over and away from the opening which it spans, and takes up no space except along the line of approach to the bridge.

The Millwall Dock bridge (Plate 8, Fig. 8) is the ordinary form of traversing bridge spanning a single opening; it has a counterbalancing tail-end, and is worked by hydraulic machinery. In order to open the passage, the bridge is first lifted, as shown by dotted lines, to the level of the approach roadway, and it is then rolled back, by the aid of rollers underneath, till it is drawn clear of the passage.

When a traversing bridge forms part of a viaduct it is possible to avoid waste of material by making the traversing portion span two openings. The portion of the girder across the space to be opened is made the heaviest, and its end placed upon movable supports. When the bridge is to be rolled back, these supports are lowered, raising the other end which is then drawn up along the viaduct; and the movable bridge is rolled along the viaduct and the central pier, till it clears the opening, its end finally resting on the central pier.

Lift-Bridges. Bridges have been constructed which can be raised entirely from their supports to a certain height, and thus afford an increased headway for vessels passing underneath. They are termed lift-bridges. This type of bridge has been very rarely adopted; and, as the whole weight of the bridge has to be lifted, the system is not applicable to large spans. Perhaps the best known example is the bridge erected over the Surrey Canal, in 1849, for carrying a branch of the Brighton railway [1], where an ordinary swing-bridge could not be adopted, owing to the special wording of the Act, authorising the line, which prevented the compulsory purchase of any land from the Canal Company beyond the actual amount required for the line itself. Wire ropes, passing over large

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. ix, p. 303.

wheels fixed at the top of cast-iron standards, were fastened to the four corners of the bridge and served to lift it.

Pontoon Bridges. This class of movable bridge consists of a floating portion which can be drawn into or out of position.

One of the best and most recently constructed examples of this system is the movable portion of the large pontoon bridge erected, by Mr. Leslie, across the river Hooghly, in 1873–4[1]. The movable portion is situated in the centre of the bridge, and is composed of two sections, each resting upon two long iron pontoons which, like the pontoons supporting the remainder of the bridge, are firmly moored in position. When the bridge is to be opened, the movable sections are first warped together up stream far enough to be clear of the rest of the bridge, the two sections are then disconnected and drawn to one side, in opposite directions, so as to leave a perfectly clear passage in the line of the opening. The opening, formed by the removal of the two sections, and by raising projecting drawbridges at each extremity of the fixed portions, has a width of 200 feet. The bridge can ordinarily be opened in fifteen minutes, and closed in about twenty minutes.

This system possesses the advantage of enabling any sized opening to be provided with little additional trouble.

Of the various types of movable bridges, swing-bridges moved by hydraulic machinery are undoubtedly the best; and, generally speaking, any of the other types should only be resorted to when swing-bridges are inapplicable owing to special conditions.

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. liii, p. 2.

CHAPTER XI.

HISTORY OF INLAND CANALS.

English Canals. Scotch Canals. Irish Canals. Other Canals in Europe. Indian Canals. Chinese Canals. American Canals. Canadian Canals. Comparison between Canals and Railways. Advantages possessed by Canals in some respects, and for certain kinds of merchandise. Value of Canals as supplementary channels of communication.

English Canals. The introduction of canals may be traced back to remote periods: thus in England the Romans constructed the Caer Dyke and the Foss Dyke; and canals existed in Egypt and China before the Christian era. Some remains only of the Caer Dyke are in existence at the present day; it extended from Peterborough to the river Witham, a distance of about forty miles. The Foss Dyke, however, is still a navigable canal; it is eleven miles long, and connects the river Trent, near Torksey, with the river Witham at Lincoln.

It is uncertain whether the Romans made these dykes for the purposes of drainage or navigation, but it appears that they were utilised for navigation at an early period. Notwithstanding the example thus set, little progress was made in the construction of canals in England till the eighteenth century, before which time canals had been introduced into other parts of Europe; and the Languedoc Canal, 148 miles long, had been constructed in France in the previous century.

River navigation in its primitive form, with little attempt at improvement, had sufficed for the requirements of inland water communication in England till a new impetus appeared

to be given to the matter about the middle of last century. About that period schemes were started for improving the navigable capabilities of the Mersey, Weaver, and other rivers. In 1737 an Act was obtained for rendering the Worsley Brook navigable to the river Irwell; and, in 1755, a project was started for forming a continuous line of water communication between the ports of Liverpool and Hull by means of a canal uniting the Trent and the Mersey.

It was, however, mainly due to the energy and capital of the Duke of Bridgewater, and the ability of James Brindley the engineer, that England was at length adequately provided with canal communication. The Bridgewater Canal, from Worsley to Manchester, was the first of a series of canals constructed by Brindley. The Barton aqueduct, for carrying the canal over the river Irwell at a height of 39 feet above the river, was the first work of the kind in England, and its erection was much objected to at the time as a wild project; but it proved perfectly successful, and saved a large portion of the expense that would have been incurred if the original plan had been adhered to, namely, carrying the canal down from the Worsley coal mines to the Irwell by a flight of locks, and then bringing it up again in a similar manner on the opposite side. The canal was completed in 1761. Numerous canals were constructed in different parts of the country as soon as the success of the earlier works was assured; one of the most important of these being the Grand Trunk Canal, which starts from the river Mersey at Runcorn, and connects it with the Trent at Wilden Ferry; it was commenced in 1766, and completed in 1777, and is 96 miles in length. The canal is 18 feet wide at the bottom, 31 feet wide at the top, and $5\frac{1}{2}$ feet deep. The most important work on the canal was the Harecastle Tunnel at the summit-level, 2888 yards long, 12 feet high, and 9 feet wide; it occupied eleven years in construction owing to the inexperience in tunnel work at that period. The tunnel, however, was barely large enough to allow a

moderately laden barge to pass through; and, eventually, owing to the increase of traffic, it was found necessary to make a second tunnel parallel to the first. This tunnel, executed under Telford's directions, was made 16 feet high and 14 feet wide, and was completed in 1827, within three years of its commencement. The Grand Trunk Canal was subsequently connected with the Severn, according to Brindley's scheme, by the Staffordshire and Worcestershire Canal, thus forming a line of water communication between Liverpool, Hull, and Bristol. Eventually, canals were constructed connecting the Grand Trunk Canal with the Thames at Oxford; and as the Thames had been made navigable up to Oxford as early as 1624, London was finally connected, by inland canals, with the other three principal English ports. The chief inland towns were soon connected together, and to sea-ports; and canals were gradually extended, till the advent of railways stopped their progress and checked their prosperity.

There are 2800 miles of canals in England, and 2500 miles of navigable rivers. The smaller canals are 4 feet deep, 12 feet wide at the bottom, and 24 feet at the surface of the water; whilst the ordinary dimensions are, 5 feet depth, 25 feet bottom width, and 40 feet surface width.

Scotch Canals. Though the canals in Scotland are much fewer in number than in England, some of them are on a larger scale. The largest of these, namely the Caledonian and Crinan Canals, will be referred to in the next chapter. The Forth and Clyde Canal, designed by Smeaton, was carried out during the same period that so many English canals were being made, having been commenced in 1766, but, being delayed by the American War and want of funds, it was only completed in 1790. It was, however, on a larger scale than the English canals of that period, having a bottom width of 27 feet, a surface width of 56 feet, and a depth of $8\frac{1}{2}$ feet, which was subsequently increased to 10 feet by raising

the banks. With its branches to Glasgow and Monkland, it has a total length of nearly 39 miles; its summit-level is 156 feet above the sea, and it has 39 locks. By the construction of the Union Canal, completed in 1822, 5 feet deep and 38½ miles long, which joins the Forth and Clyde Canal near Falkirk and extends to Edinburgh, direct water communication was afforded between Edinburgh and Glasgow.

Irish Canals. The principal canals in Ireland are the Grand and Royal Canals, each 6 feet deep and about 24 feet wide at the bottom. The Grand Canal was commenced in 1765. It extends from Dublin to the Shannon, which it enters near Banagher, and proceeds on the opposite side of the river to Ballinasloe, the distance being altogether 99 miles. Its summit-level is 200 feet above the sea. It has several branches, raising its total length to 164 miles. It runs through the bog of Allen, which occasioned a large expenditure. The Royal Canal was commenced in 1789. It, also, goes from Dublin to the Shannon, joining it near Tormanbury, running in a slightly northerly direction; whilst the Grand Canal runs nearly due west from Dublin. The Royal Canal is 92 miles long, and rises to a height of 322 feet above the sea at its summit-level.

There are 300 miles of canals in Ireland.

European Canals. The Italians appear to have taken the lead in constructing canals in Europe, as they made irrigation canals as early as the twelfth century, and rendered the Navilio Grande Canal navigable in 1271. The invention of the pound-lock, which effected a great transformation in inland navigation, is believed to have originated in Italy, and was introduced into France by Leonardo da Vinci, whom Francis I summoned to his aid. The first French canal, constructed with locks and having a summit-level, was the Brière Canal, 34½ miles long, connecting the Seine and the Loire; it was commenced in 1605 and completed in 1642. The principal French canals have been constructed for con-

necting two rivers together, by surmounting the water-parting which separates their valleys, so as to complete a regular chain of inland navigation. Thus the Canal du Centre connects the Loire and the Saône; the Bourgogne Canal connects the Seine and the Rhone; the Saint Quentin Canal connects the Scheldt and the Somme, and the Rhone and Rhine Canal unites the two rivers from which it derives its name. The Eastern Canal is under construction at the present time, for the purpose of restoring the communication between the Meuse and the Saône, which was lost to France by the annexation of Alsace and Lorraine to Germany; and the work is being also prolonged northwards along the Meuse, to the Belgian frontier near Namur, so as to open direct communication with the Belgian coal-fields. Many of the French canals have a depth of only 5 feet of water; but the new canals are being made deeper, and it is proposed to deepen by degrees the canals forming the main lines of water communication. Thus the Eastern Canal is being given a depth of 6 feet 7 inches, or an available depth of 5 feet 11 inches; and the Marne-Rhine Canal, which was originally $5\frac{1}{4}$ feet deep, is being deepened to the same extent. The locks also vary considerably in size, from about 13 feet 9 inches in width to 19 feet 8 inches, and from 65 to 164 feet in length. The inconveniences arising from this want of uniformity become greater as the connection between the canals is extended, and resemble for the larger vessels a break of gauge. New locks are to be constructed to a uniform type, 17 feet in width and not less than 131 feet long; the width selected being that to which many locks had been previously made. An excellent account is given of all the canals in France by M. Krantz in his series of Reports to the National Assembly between 1872 and 1874. At the outbreak of the French Revolution last century there were 663 miles of canals in France; whilst in 1870, there were 2954 miles of canals, 2065 miles of canalised rivers, and 1871 miles of uncanalised rivers,

making in all 6890 miles of inland navigable water communication in France. The cost price of the French canals is estimated to amount altogether to £11,600 a mile, and of the canalised rivers to £4800 a mile. M. Krantz considered that a further expenditure of £33,300,000 would be eventually required to perfect the lines of inland navigation in France, of which sum, however, he proposed that only £17,440,000 should be defrayed in the execution of certain works to be commenced forthwith, amongst which was the Eastern Canal already alluded to. Of the above amount, £6,040,000 would be required for improving existing lines of water communication, and £11,400,000 would be expended in opening new lines; the first sum, it is proposed, should be provided wholly by the Government, and the latter expense shared between the Government and the landed proprietors who would be benefited.

The canal system has been more largely developed in Holland than in any other country of Europe. The flatness of the country, and the abundance of water owing to the low level of the land, render canals easy to construct and cheap to maintain; and the necessary cleaning out of the canals to preserve their depth is readily performed for the sake of the deposit of mud which is valuable as manure. Canals were commenced in Holland and Belgium in the twelfth century; they enabled Flanders to become the centre of commerce about the fourteenth century, and they have frequently been extended up to the present time. The canals are generally about 60 feet wide and 6 feet deep. Being for the most part without locks, except at their outlets, they realise in perfection the requirements of inland navigation. They serve as the highways of traffic throughout the country. In Amsterdam the number of canals nearly equals the number of principal streets, as they intersect it in every direction; for the city being in the shape of a half circle, the canals are arranged in concentric half rings which are connected together by a series

of other canals arranged radially. Other towns also in Holland are amply provided with canals. The Dutch canals, however, with the exception of the larger class to be hereafter referred to, present less interest, from an engineering point of view, than canals situated in less favourable districts. The value, indeed, of canal works as examples of engineering skill varies approximately in proportion to their cost, whilst commercially the exact reverse is the case. The Dutch canals have in general proved very remunerative undertakings, and gave the Netherlands an importance in Europe in the middle ages quite disproportionate to the extent of the country.

Canals have been constructed in the other countries of Europe, but they have not been carried out on so extended a scale as in the countries already referred to. The geographical position of Spain renders irrigation canals as important for that country as for Italy; but though irrigation works were carried out by the Moors in the ninth or tenth centuries, and Charles V commenced the large Aragon Canal in 1528, little progress was made in the intervening periods up to nearly the close of last century, when the Aragon Canal was completed and other works commenced. The Henares and the Esla Canals, which had been contemplated about the same period, were commenced in 1863 and completed about 1868[1]. The Henares Canal, 28 miles in length, is capable of irrigating 27,000 acres; whilst the Esla Canal is capable of irrigating 32,000 acres, and its construction cost only half the amount of the other.

The most recent large irrigation work in Italy is the Cavour Canal, which was commenced in 1862, and cost £4,104,000. The canal starts from the river Po, not far from Turin, and terminates in a junction with the river Tessin above Novara; it is 51 miles long, and has a total fall of 71 feet. When the canal had been completed, as originally designed, it was discovered that the summer

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxvii, p. 483.

discharge of the Po had been considerably over-estimated; and a canal had to be constructed for bringing a supplementary supply from the Dora Baltea which, rising amongst the glaciers of the Alps, possesses fortunately a large discharge in the summer when the Po is low.

Indian Canals. The necessity of obtaining a supply of water for the land, during the dry season, in many parts of India, for the purpose of averting famines or improving the productiveness of the soil, has led to the construction of numerous irrigation canals. Most of the large irrigation canals have been constructed so as to be available for navigation; and some canals, especially in southern India, have been formed solely for navigation. These latter, of which the Buckingham Canal, going from Madras to the Kistna delta, and the canal running along the Malabar coast, are instances, have been constructed for the most part with little difficulty.

The largest irrigation work in India is the Ganges Canal, for irrigating the district between the Ganges and the Jumna, opened in 1854. The canal with its main branches is about 650 miles long, and it is capable of irrigating an area of 1,205,000 acres; it had cost, up to 1878, the sum of £3,055,000. Soon after the canal was opened, it was found that the slope of the canal had been made too great, so that the velocity of the current caused a scouring action on the sandy bottom of the canal, and that the head-works of the canal were inconveniently placed. The canal was accordingly remodelled about twelve years later; and an extension, known as the Lower Ganges Canal, was proposed to supplement the original canal. The Lower Ganges Canal, now in course of construction, is designed to have a total length of 582 miles; and the estimated cost is £3,768,000, of which £1,267,000 had been expended in 1878. The other principal irrigation canals in the North-West provinces are the Agra and the Eastern Jumna Canals. The Agra Canal, opened in 1874, draws its supply from the Jumna at Okhla,

ten miles below Delhi: it irrigates 375,800 acres of land, and cost £804,500; the main canal is 140 miles long. The Eastern Jumna Canal was originated by the native Government in the seventeenth century; it was restored by the British Government in 1823-30, and further improved in 1854.

There are several important irrigation works in other provinces of India, as for instance the Orissa and Sone Canals in Bengal; the Madras Irrigation Canal, the Godavery and Kistna Delta Works in the Madras Presidency; and the Bari Doub, Sirhind, and Western Jumna Canals in the Punjaub. The Western Jumna Canal appears to have been commenced in very early times, a canal in that district having been made in the fourteenth century. The works, which were subsequently extended, became useless for want of repair about the middle of last century. Its restoration, commenced in 1817, was the first irrigation work undertaken by the British Government, who reopened 290 miles of the old native canals and added 143 miles of new canals to the main lines.

Some idea may be formed of the large extension of irrigation works that has been accomplished by the Government, in recent years, by the fact that a sum of £10,570,000 has been expended on these works between the years 1867 and 1878. A detailed account of the Ganges Canal has been written by its designer Sir Proby Cautley; and a concise account of the various irrigation canals will be found in Mr. R. B. Buckley's book on 'The Irrigation Works of India.'

The works have not always yielded the large return anticipated, though it is stated that, taken as a whole, they pay about 5 per cent. interest on the actual cost. This, however, is mainly due to the large revenue derived from seven of the most successful works, namely, the Sind, the Ganges, the East and West Jumna, the Cauvery, the

Godavery, and the Kistna irrigation works, which, taken together, yield a profit of 10 per cent., after paying the working expenses and 4½ per cent. interest on capital. The rest of the works, with an expenditure of capital amounting to about double that of the seven enumerated above, paid up to 1876 little beyond their working expenses. Nevertheless it is expected that the return from many of these will become more satisfactory when they have had time to be properly developed, and when their utility has been fully recognised.

Chinese Canals. The Chinese constructed canals, partly for irrigation and partly for navigation, at a very early period. The largest and most celebrated of these is the Grand Canal, 650 miles in length; it commences at Hang-Chow, and terminates at Lin-tsing on the Euho river, crossing in its route the large rivers Yang-tsze-keang and Hwang-ho. As the Euho joins the Peiho river, internal water communication exists between Hang-chow and Pekin. Though its execution must have involved a vast amount of labour, there is little display of engineering skill in its construction, beyond large embankments and cuttings combined with a winding course so as to maintain its level nearly uniform; and the depth of water in it seldom exceeds 6 feet. Although China has been sometimes given the credit of being the first country in which the pound-lock was introduced, it does not appear that it has ever been adopted in that country; whereas the methods of stop-gates and inclined planes have been used for passing boats from one level to another. The Grand Canal is said to have been begun towards the close of the thirteenth century by the Emperor Chi-Tso. It has seventy-two wooden stop-gates, for reducing the rate of the current and raising the water-level.

American Canals. There are several canals in North America, some of them being of considerable magnitude and serving to connect together the vast natural inland

lake and river navigations[1] (Plate 10, Fig. 3). The most important of these works is the Erie Canal, begun in 1817 and completed in 1825; it starts from Buffalo at the east end of Lake Erie, and extends to Albany, where it joins the Hudson river, thus establishing a line of inland water communication between Lake Erie and New York. The canal is 352 miles long, and was originally constructed 40 feet wide at the water surface, 28 feet wide at the bottom, and 4 feet deep, so as to accommodate vessels of 60 tons; but it has since been enlarged so that vessels of 240 tons can navigate it, having been made 70 feet wide at the water surface, from 52 to 56 feet wide at the bottom, and seven feet deep. It has seventy-one lift-locks, and two regulating locks, having a total lift of 654 feet. The locks, 110 feet long and 18 feet wide, were originally made single, but they were subsequently doubled by constructing a second lock parallel to the first. A branch canal, 38 miles long, starting from the main canal near Syracuse and going to Oswego, connects the main canal with the eastern end of Lake Ontario; and the Champlain Canal, 66 miles long, commencing at Albany, connects it with Lake Champlain.

The Chesapeake and Ohio Canal, designed on the same scale as the enlarged Erie Canal, was projected for the purpose of joining the Potomac near Georgetown with the Ohio at Pittsburg, the total length being 341 miles. Though, however, the proposed route was surveyed in 1825, and was commenced in the valley of the Potomac in 1828, it was only completed as far as Cumberland by 1850, a distance of 186 miles; and no further progress has since been made. Fresh surveys were ordered by the United States Government in 1873, with the object of ascertaining the best route for the extension of the canal to Pittsburg, and especially the easiest way of crossing the ridge of the Alleghany range of moun-

[1] Notes on some of the Chief Navigable Rivers and Canals in the United States and Canada, by T. Walch.

tains. Colonel Merrill reported, in 1875, that inclined planes must be resorted to for conveying the traffic on the canal from Cumberland to the summit-level[1]. It is proposed to make a tunnel at the summit-level, $3\frac{3}{4}$ miles long, having a height of 28 feet, and a width of 46 feet, so as to enable the traffic to pass through it in both directions at the same time. The ascent from Cumberland to the summit-level is to be accomplished by seventeen inclined planes, rising altogether a height of 1185 feet. The descent on the western slope, being much more gradual, will be effected by means of six inclined planes and fifty-six locks. It is intended to transport the boats, on the inclines, in caissons in which they can float, upon the principle previously described as carried out on the Monkland Canal incline, and recently adopted at an incline, constructed in 1876, for connecting this very canal with the Potomac at Georgetown, in the place of a flight of five locks originally placed there.

The Morris Canal, connecting the River Delaware at Philipsburg with the Hudson river at New York, is chiefly interesting on account of the inclined planes which were adopted for surmounting the very rugged country which it traverses. It is 102 miles long, and crosses, at its summit-level, a spur of the Alleghany range, where it is 760 feet above the Delaware river, and 914 feet above mean-tide level in the Hudson river. The differences of level are surmounted by twenty-three locks, having a total lift of 225 feet, and twenty-three inclines, having a total rise of 1449 feet. The boats are carried along the inclines on cradles, as previously mentioned. The canal was commenced in 1825, completed in 1831, and enlarged between 1841 and 1845, so as to be capable of conveying boats of 44 tons. The traffic having steadily increased from 1845 to 1860, the canal was again enlarged in the latter year, so as to accommodate boats of from 70 to 80 tons; but since 1866 the

[1] Report of the Chief of Engineers (United States) for 1875.

competition of the Lehigh Valley Railway produced a decline in its traffic, which has been further promoted by the canal being leased to the railway, so that now the canal is of little importance.

The Illinois and Michigan Canal, starting at Chicago on the river of that name close to Lake Michigan, and terminating at La Salle on the Illinois river, connects Lake Michigan with the Illinois river which, flowing into the Mississippi, forty miles above St. Louis, completes the line of inland water communication between the lakes and the Gulf of Mexico. The canal is 60 feet wide at the water surface and 40 feet at the bottom, and 6 feet deep. It was completed about 1846, but unfortunately its value has been hitherto much impaired by the shallowness of the Illinois river in dry seasons. The river, however, is now undergoing improvement, by the erection of dams for raising the water-level, and by dredging.

Canadian Canals. Though the river St. Lawrence and the chain of large inland lakes furnish Canada with the finest natural inland navigation in the world, it has been found necessary to improve and complete short portions, by six short canals, along the line of the river St. Lawrence, between Lake Ontario and Montreal, which are known as the St. Lawrence Canals, and by the Welland Canal, constructed to avoid the break in the communication between Lakes Erie and Ontario caused by the falls of Niagara. The St. Lawrence Canals are together 43½ miles long, and were completed between 1843 and 1848. The locks, twenty-seven in number, have a total lift of 206½ feet, and are 200 feet long, from 45 to 55 feet wide, and have a depth of 9 feet of water on the sill. The Welland Canal, having a length of 27 miles, extends from Lake Erie to Lake Ontario in a direction parallel to and to the west of the Niagara river. It has twenty-seven locks, with a total lift of 330 feet. It was opened, in 1833, to accommodate small vessels, but was

enlarged, in 1867, so as to afford a passage to vessels of 400 tons (Plate 10, Fig. 3).

The increased size of the vessels which it is found economical to employ for navigating the lakes, has of recent years necessitated a transhipment of goods at the eastern end of the Erie Canal, as the greater number have been unable to pass through the Welland Canal. This circumstance has tended to cause the greater portion of the lake traffic to go to New York from Buffalo by railway, or by the Erie Canal. In order to divert this large and constantly increasing stream of traffic to Montreal, where it can be shipped in the largest class of ocean-going steamers, it was decided, in 1871, to improve the canals between Lake Erie and Montreal. The works on the Welland Canal were commenced in 1874, and are approaching completion; whilst the enlargement of two of the St. Lawrence Canals is in progress The bottom width of the channel is to be 100 feet, and the available depth 14 feet. The locks on the enlarged canal are to be 270 feet long between the gates, 45 feet wide, and to have a depth of 14 feet of water on the sills. According to the report, in 1880, of Mr. John Page, the chief Engineer of Canals in Canada, the canals, when completed, will enable vessels of 1000 tons of the ordinary build to pass from Lake Erie to Montreal; and vessels of greater breadth of beam, capable of carrying 1500 tons, will probably ere long follow this route. The cost of the new works on the Welland Canal is estimated at £2,310,000; and the enlargement of the St. Lawrence Canals at about £2,000,000. The importance that this route will attain, when completed, is sufficiently assured by the fact that any port on the lakes is 480 miles nearer Liverpool by the Montreal route than by New York.

The Rideau Canal, connecting the river Ottawa at Ottawa with the St. Lawrence at Kingston, was constructed by the British Government, between 1826 and 1832, for military purposes: it is 126 miles long, and was formed for most of

its length by canalising the rivers Rideau and Cataraqui. The only other Canadian canals of some importance are the canals for improving the navigation of the Ottawa river between Ottawa and the St. Lawrence, into which it flows at Montreal, and the Richelieu Canals which complete the navigation of the Richelieu river from its junction with the St. Lawrence, at Sorel between Montreal and Quebec, to Lake Champlain. These latter canals form the final links of a very direct inland water communication from New York to the St. Lawrence.

Comparison of Canals and Railways. It will be seen from the above historical sketch, and especially from the recent extension of canals in France and America, that canals are by no means the antiquated relics of the past that the condition into which internal navigation in England has fallen might lead persons to suppose. It is evident that rivers and canals, when properly maintained and developed, still form important routes of inland communication. Their commercial value has in most cases been considerably impaired by railways; but they are gradually recovering from the depression into which they were thrown by the keen competition of the railway systems. Though canals cannot hope to compete with railways in the conveyance of passengers and of light and perishable articles, owing to the comparatively slow rate of transit on canals, it is certain that they possess advantages for the transport of heavy and bulky goods.

From an interesting comparison, made by M. Malézieux[1], between the amount of goods conveyed by railways, and by inland navigation in France, in the year 1872, it appears that out of about 100 million tons of merchandise 43 million tons were carried by water.

In addition to great speed in transit, railways possess the superiority over canals of being capable of being constructed across almost any country; whereas canals can only be

[1] Cours de Navigation Intérieure. M. Malézieux. Part i. p. 13.

economically made through tolerably level districts, and where a supply of water can be procured at moderate cost. Also, generally, railways follow a more direct course than rivers and canals.

Canals, however, possess some important advantages over railways: they frequently are less costly in construction, and their cost of maintenance and their working expenses are considerably smaller. Moreover, the proportion of dead weight to the load carried is much less in canal barges than in railway wagons; and the barges not only cost much less proportionately to their capacity than wagons, but are also far more easily repaired. The resistance also to traction is much smaller in water than on rails, amounting, according to M. Malézieux, to only one-fifth of the average resistance on railways. Barges on canals can be loaded or unloaded at any places which they pass; whilst goods trains can only stop at the stations. The combined effects of these circumstances enable canals to carry certain classes of merchandise more cheaply and conveniently than railways.

Canals, if maintained, extended, and, when necessary, enlarged, as is being done now in France, and if not suffered to fall into the hands of the proprietors of railways traversing the same districts, both foster a healthy competition with railways, and tend consequently to reduce the cost of transport to the advantage of the public. They also are valuable in supplying channels of relief for the surplus traffic already overstraining the carrying capacities of some of the existing lines of railway.

CHAPTER XII.

SHIP-CANALS.

Four different classes of Ship-Canals: 1. Ship-Canals with Locks and a Summit-Level; Languedoc Canal; Caledonian Canal. 2. Ship-Canals in Low Districts, with Regulating Locks: North Holland Canal; Amsterdam Canal. 3. Ship-Canals without Locks, and of world-wide importance: Suez Canal; Panama Canal. 4. Ship-Canals from Inland Ports, and Lateral Canals: Gloucester and Berkeley Canal; Canals from Bruges to the sea; Ghent-Terneuzen Canal; Lateral Canals.

THE object of Ship-Canals is mainly to connect two seas together by a line of water communication, and thus open out a shorter course for sea-going vessels. The utility of these canals depends upon the amount by which they shorten the distance between various ports, and the class of vessel they are capable of accommodating: their importance depends upon the amount of traffic which is induced to pass through them, which is much influenced by their situation and accessibility; and their interest, from an engineering point of view, depends upon the magnitude and novelty of the works they necessitate. The value of such works, especially if suited to accommodate large vessels, is generally independent of the extension of railways; and, indeed, in the case of the Suez Canal the opening of the canal rendered the railway across the isthmus comparatively useless, and a similar fate very likely awaits the railway across the isthmus of Panama. Isthmuses, or comparatively narrow necks of land intersected by lakes or rivers, are the natural fields for such enterprises.

There are three distinct classes of ship-canals, and a fourth supplementary class.

1st, Canals which traverse an ordinary tract of country and surmount the water-parting of two adjacent basins, stretching down to opposite shores. They rise gradually, by means of locks, from the sea on the one side, till they attain the summit-level, and then descend, in a similar manner, to the opposite coast. In such canals the route of least elevation is chosen, as well as where rivers or lakes can be included in the channel of communication. The Languedoc Canal, crossing the south of France and uniting the Bay of Biscay to the Mediterranean Sea, is the earliest instance of such a work; and the Caledonian Canal, forming a connection between the North Sea and the Atlantic Ocean through the centre of Scotland, is the finest example of the kind existing in Great Britain.

2nd, Canals which pass through a level low-lying district, such as Holland, and only require locks at each extremity to adjust the varying levels of the sea to that of the canal. The North Holland Canal and the Amsterdam Ship-Canal are instances of this class.

3rd, Canals which unite two seas by merely forming an open artificial water channel, at one uniform level, through the isthmus separating them, without the intervention of locks or any obstacle to free navigation. The Suez Canal is a grand instance of this type of canal; and the projected Panama Canal is to be constructed on the same principle.

4th. There is in reality a fourth class of ship-canals distinct from the other three. This is the class of canal which either provides a short cut to the coast for a port, somewhat inland, possessing a circuitous river communication with the sea, or which restores a deep-water access to the sea to a port whose natural means of communication has been impaired by silting up. It forms, indeed, a sort of connecting link between inland and ship-canals, differing from the former merely in the larger

size of the works, and from the latter in not connecting two seas. The Ghent-Terneuzen Canal is an example of this class of canal; and the proposed canal from Bruges to Heyst on the North Sea is similar in design. In this class also must evidently be included large lateral canals, taking the place of rivers the regularity of whose flow, or the directness of whose course, or whose outlet, is defective; as for instance the St. Louis Canal, which has superseded the lower Rhone navigation, and the Gloucester and Berkeley Canal, which furnishes a better approach to Gloucester than the river Severn can afford.

1. Ship-Canals with Locks and a Summit-Level.

The first class of ship-canals resemble in principle, though they differ in magnitude and accommodation from, the ordinary inland canals joining two river navigations flowing into different seas; such as the Trent and Mersey Canal, and the Thames and Severn Canal. The object, however, of these latter canals has been merely to unite and extend two river navigations; whilst ship-canals have been designed with the primary purpose of shortening the voyages of sea-going craft. Whereas inland canals can be extended in many directions, the sites suitable for ship-canals are comparatively few. The nature of these undertakings will be sufficiently illustrated by brief descriptions of the Languedoc and Caledonian Canals.

Languedoc Canal. This canal, known now in France as the 'Canal du Midi,' or the 'Canal des deux mers,' possesses a peculiar interest as being the earliest existing example of a canal designed to connect two seas. The scheme was proposed in the reign of Francis I, but it was not executed till the reign of Louis XIV. Its object was to form a line of water communication between the east and south coasts of France, which should dispense with the necessity of vessels, trading between these parts, making the long round through the Straits of Gibraltar (Plate 9, Fig. 1). Natural water com-

munication existed from the Bay of Biscay, by the rivers Gironde and Garonne, up to Toulouse; so that it was only necessary to construct a canal between Toulouse and Narbonne on the Gulf of Lyons.

The canal, whose construction was authorised in 1666, was completed in 1681, considerable delay having been occasioned by the absorption of government funds in wars. It was designed and carried out by Riquet.

The summit-level, at Naurouse, is 610 feet above the Mediterranean. According to Lalande[1], eight single locks and nine double locks were constructed between the canal's junction with the Garonne and the summit-level; and twenty-eight single locks, ten double locks, five triple locks, one flight of four locks and one flight of five, from the summit-level down to the Mediterranean. The average lift of each lock is 7 feet 9 inches; but some locks were made with only a 5 feet lift, and others with a lift of as much as 12 feet. The total length of the canal, as originally constructed, was about 140 miles, but its present length, including branches, is 171 miles, according to M. Krantz[2]. There are now 119 locks on it, each having a length of 102 feet and a width of 19 feet 8 inches. The depth of water in the canal is fixed at 6 feet 7 inches. The canal, as constructed, passed in aqueducts over fifty-five rivers and streams which crossed its course; and there are 118 bridges over it.

The canal is supplied with water by the rivers Orb, Herault, and a tributary of the Aude, and at its summit-level by the reservoirs of Lampy and St. Féréol. The supply provided has occasionally not sufficed throughout a very dry season; but, with the Pyrenees so near, it could be easily augmented at a moderate cost. The cost of the canal amounted to £1,440,000. The principal port of the canal on the Mediterranean is the harbour of Cette.

[1] Traité des Travaux de Navigation. M. de Lalande 1778, p. 35.

[2] Rapport à l'Assemblée Nationale, par M. Krantz, 1874, No. 2177, p. 60.

The traffic upon the canal has been reduced by about one-half since 1847, in consequence of the competition of the Southern railway, which has succeeded in diverting the traffic; and the carriage of bulky and heavy goods, which could be best performed by the canal, is prevented by the high rates which were imposed when the canal possessed a very valuable monopoly. The canal is the joint property of the State and of some private individuals. M. Krantz considers, that if the State bought out the other proprietors, and then reduced the rates and prolonged the canal southwards along the Mediterranean coast to Perpignan and La Vendre, the value and the returns of the canal might be considerably increased.

The canal appears to have been a very prosperous undertaking in former times, having had the good fortune to be established long before the introduction of railways. Besides forming a short cut between the eastern and southern coasts of France, it opened up a valuable district. The fact of its having succumbed in the competition with railways is easily accounted for. It was constructed in the days when the size of trading vessels was comparatively small. Moreover, the character of the country and the elevation of the summit-level of the canal would have rendered the enlargement of the canal, to suit the present requirements of vessels, unadvisable, owing to the enormous cost of such an undertaking, and the serious impediment such a number of locks must necessarily present to the passage of vessels. Accommodation for large vessels and an unimpeded course are the conditions now needed for ship-canals, and these the Languedoc Canal is incapable of affording. The size of sea-going vessels and the speed of conveyance have entirely changed since the establishment of the canal, and consequently it has lost much of its former importance. Nevertheless it remains a wonderful monument of engineering skill at a very early period; and, considering the interest the French always take in developing

to the utmost the resources of their means of water communication, it is quite possible that it may regain eventually a portion of its lost traffic.

Caledonian Canal. There is a remarkable valley, called the Great Glen of Scotland, stretching across the Highlands of Scotland, between Inverness Firth on the east coast and Fort William on Loch Eil on the west coast, which, with the exception of twenty-two miles, is occupied by a chain of lochs (Plate 9, Fig. 2). In 1773 James Watt was requested by the Commissioners of Forfeited Estates, in whose hands the valley then was, to report to them on the practicability of opening out a navigable communication between the several lochs and the inlets connected with the eastern and western seas. He reported favourably on the scheme; but the estates being restored in 1784, the scheme was dropped. It was, however, revived again at the commencement of the present century, when the Government, being desirous of improving the means of communication between the eastern and western coasts of Scotland, obtained a report from Thomas Telford with reference to the proposed Caledonian Canal[1]. The Government were led to this undertaking by the expectation that the canal would save vessels a long and dangerous circuit by the Pentland Firth, where, previous to the introduction of steam, they were liable to be detained for weeks by contrary winds and stormy seas; and also that in time of war the canal would afford a convenient refuge for merchant vessels from privateers, and a way for vessels of war to effect a rapid passage from one sea to the other.

Telford was entrusted with the carrying out of the work, which was commenced in 1804 and completed in 1823 (Plate 10, Fig. 1). The canal commences on the east side at the village of Clachnacharry on the Beauly water, an inlet from the Inverness and Moray Firths, through which it is connected with the North Sea. The canal was designed

[1] Life of Telford, pp. 49 and 297.

for vessels of 20 feet draught; and the locks are 170 to 180 feet in length and 40 feet wide, and have a rise of 8 feet. The canal is entered through a tide-lock, and is enclosed between artificial banks till it reaches high-water mark, where another lock has been made. A little further on a rise is effected by a flight of four locks, known as the Muirtown Locks, and from thence the canal, 50 feet wide at the bottom, 120 feet wide at the water-level, and 20 feet deep, is carried along in a level reach to Loch Ness, but having to traverse, for a portion of its course, the bed of the river Ness, a regulating lock had to be introduced. Loch Ness is about 22 miles long, and of ample depth. On leaving Loch Ness the canal rises to Loch Oich, which is the summit-level, by a flight of five locks and a single lock, a regulating lock having to be introduced in addition. Issuing from Loch Oich the canal descends to Loch Lochy, a distance of two miles, through an ordinary lock and another regulating lock placed near the entrance to Loch Lochy. At the other end of Loch Lochy, which is ten miles long, there is again a regulating lock; and then the canal proceeds in a level reach to within a mile of Loch Eil, where it descends by a flight of eight locks, called Neptune's Staircase; and descending again through two locks at Corpach, it enters Loch Eil through a tide-lock which places it in communication with the Atlantic Ocean. The total distance from one extremity of the canal to the other is sixty miles, of which about thirty-eight miles are natural lake navigation. The summit-level is about 100 feet above the sea. The total cost of the works was about £1,000,000. The lakes and rivers along the route of the canal, which receive the drainage of the valley, afford an ample supply of water to the canal, so that all difficulties in this respect were avoided by the judicious choice of site. Regarded merely as an engineering work the canal was a bold and skilful undertaking, very judiciously planned and successfully carried out, but it has

not proved a commercial success. The wars at the commencement of the century hindered the prosecution of the canal; and the great increase in the value of materials and labour during the progress of the works raised the cost of the canal to nearly double the sum at which it was originally estimated. It had been intended to make the canal 50 feet wide at the bottom, 122 feet wide at the top, and 20 feet deep; and had these dimensions been adhered to throughout, the canal would have admitted vessels of 1000 tons burden. In order, however, to complete the canal quickly at the last, and to save expense, the canal was not carried down to its proper depth through the shallow portions of Loch Oich, and through the cutting at the summit-level; and, accordingly, it can only afford a passage to vessels drawing 17 feet of water and of 250 to 300 tons burden. Moreover, it has not attracted the traffic that was anticipated; and occasionally the yearly expenditure has exceeded the receipts. Telford attributed the absence of traffic to the stoppage of trade with the Baltic, owing to the heavy duty imposed upon Baltic timber whilst Canadian timber was exempted from duty; but probably the introduction of railways, the employment of steam for navigation, and the increased size of sea-going vessels, have also largely contributed to render the traffic along the canal so small. The Languedoc Canal, though a much smaller canal in depth and width, has had the advantages over the Caledonian Canal of passing through a fertile district, of reducing to a much greater extent the distance by water between the two seas which it joins, and of having been constructed long before railways arose to draw off its traffic.

The Crinan Canal, across the peninsula of Kintyre, 9 miles long and 12 feet deep, enables vessels of 160 tons burden to save a circuit of about 70 miles round the Mull of Kintyre.

The Holstein Canal, connecting the river Eyder with Kiel Bay, is another instance of a small ship-canal. It

forms a short and convenient passage for small vessels, across Holstein, between the North Sea and the Baltic.

2. Ship-Canals passing through low-lying districts, and with only a regulating lock at each end.

In this class of canal, passing through low-lying districts, the supply of water is obtained from the sea, and the water-level is approximately the same throughout, being regulated by locks or sluices. Till recently the finest example of this type of canal was the canal extending from Amsterdam to the Helder.

North Holland Canal. The only means of access, in former times, to the port of Amsterdam was by the Texel Roads and the Zuider Zee (Plate 9, Fig. 3). The depth of water in Lake Y, in front of Amsterdam, is ample; and the run of the tide through the Texel Roads, filling and emptying the wide expanse of the Zuider Zee, maintains a very deep channel between the Texel and the mainland. The navigation, however, of the Zuider Zee is difficult, as it abounds in shoals, and there is a bar at the junction of Lake Y with the Zuider Zee. Accordingly, early in the present century the Dutch Government decided to provide a new route for vessels trading with Amsterdam. The shortest line from Amsterdam to the North Sea, in a westerly direction, was at that time considered quite out of the question, on account of the great difficulty of forming and maintaining an entrance on the exposed flat and sandy coast of the North Sea west of Amsterdam. In consequence a northerly route was adopted for the new canal, through North Holland, starting from Lake Y nearly opposite Amsterdam, and opening into the sheltered haven of Niewediep close to the deep channel of the Texel Roads (Plate 9, Fig. 3). This canal, known as the North Holland Canal, was commenced in 1819 and completed in 1825: it is 52 miles long, 123½ feet wide at

the water surface, 31 feet wide at the bottom, and 18½ feet deep (Plate 11, Fig. 4). The canal has a tide-lock at each extremity, and three intermediate passage-locks for regulating the levels of the water along the different portions of the canal and for assisting the tide-locks in ensuring the exclusion of very high tides from the canal. The two tide-locks are double, having two chambers, one for large and one for smaller vessels, which are each provided with two pairs of sea gates and one pair of gates pointing inland. The large chamber is 237 feet long and 51 feet wide, and the small chamber is 82 feet long and 18½ feet wide. The locks are built upon round bearing piles, 11 inches in diameter and 35 feet long.

The work has proved of great value to Amsterdam, and was of unusual magnitude at the period when it was executed; but it has lost a great portion of its importance since the accomplishment of the still larger undertaking, the Amsterdam Ship-Canal, which has superseded it. The chief feature of interest in the canal, at the present day, is the harbour of Niewediep, where a deep channel along the shore, from the outlet of the canal to the Texel Roads, has been secured by utilising the scour of the tidal current from the Zuider Zee. The channel has been contracted by a dyke of fascines running parallel to the shore; and another dyke, projecting outwards at an angle to the first, makes a sort of funnel-shaped opening towards the Zuider Zee, which, catching the ebbing waters as they flow from the Zuider Zee, concentrates them into the narrow channel beyond, and occasions a scouring action which maintains the channel.

Amsterdam Ship-Canal. Though the North Holland Canal had been constructed of adequate dimensions for the shipping of that period trading with Amsterdam, the continually increasing size and draught of merchant-vessels tended to divert the trade from that once famous port. The passage, moreover, between Amsterdam and the North Sea by the North Holland Canal is circuitous, and placed

Amsterdam at a disadvantage as compared with other ports, such as Rotterdam and Antwerp, more favourably situated by nature. Also the competition which has been developed, in recent years, by the rapid increase of trade and the establishment of railways, threatened to prove fatal to the commercial prosperity of Amsterdam, unless a shorter passage to the North Sea could be opened out. The shortest way to the North Sea from Amsterdam lies in a due westerly direction, through Lake Y and Wijker Meer, and across a narrow neck of land three miles wide known as the Sand-hills, which separates Wijker Meer from the North Sea, and connects Northern and Southern Holland (Plate 9, Fig. 3). This is the route which was selected for the Amsterdam Ship-Canal. The whole distance in a straight line is only 15½ miles, instead of the 52 miles along the old route.

Besides the difficulties likely to be experienced in making and maintaining a deep-water entrance on the flat sandy shore of the North Sea west of the Sand-hills, the varying levels of the Zuider Zee, with which the canal must be connected, were unsuitable for a canal; and the construction of a canal across the lakes would interfere with the drainage systems, and means of water communication, of the lands bordering on the lakes. These obstacles have been overcome by the construction of a large protecting harbour on the shores of the North Sea at the entrance to the canal, and by shutting off Lake Y from the Zuider Zee by a dam; locks being placed at each end of the canal to regulate the water-level, to exclude high tides, and to afford a passage through the dam (Plate 11, Fig. 1). The water communication and drainage of the adjacent districts has been also secured, by making branch canals communicating with the main canal, and by arranging to keep down the water-level in the canal to only 14 inches above ordinary low-water level in the North Sea. The canal has to receive the drainage of the adjacent lands and of most of the Haarlem Meer reclamation area,

which is lifted into it by pumps placed at suitable situations alongside the main or branch canals. The water thus introduced into the canal is partially let off at low water through sluiceways adjoining the locks at each end, and the remainder is raised and discharged into the Zuider Zee by pumps placed alongside the Zuider Zee locks.

The canal is 88½ feet wide at the bottom, and its sides are formed to slopes of 2 to 1; it has a depth of water of 23 feet. There are horizontal benches, on each side, a little below the water-level, which have a width of 8 feet through the sand-hills, but are increased to 98½ feet through the lakes (Plate 11, Figs. 2 and 3).

The excavations for the canal through the sand-hills were performed in the ordinary manner, being conveyed in wagons or barges to form the side banks of the lake portion of the canal. The channel was dredged out between these side banks, and the dredged material was used for raising the banks which were protected at the sides by fascines. The apparatus for discharging the dredged material, described in Chapter IV, was fitted to six out of the twelve dredging machines employed on the works, and very materially reduced the time and cost of the dredging operations. It proved of special value in the shallow parts of the lakes, where barges could not have floated; and by its aid the largest type of dredger was able to deposit 1300 cubic yards of material on the banks, in twelve hours, at a cost of about 2*d.* per cubic yard.

The North Sea locks, which are situated about three-quarters of a mile inland, are two in number; one 390 feet long and 60 feet wide, and the other 227 feet long and 40 feet wide (Plate 11, Figs. 8 and 9). Adjoining these locks is a sluiceway, 34 feet wide, for letting water out of the canal at low water. Each lock is provided with five pairs of gates; two pairs at each end pointing opposite ways, and one pair in the centre pointing towards the North Sea. The sluice-

way is furnished with two pairs of sea gates and one pair of canal gates. The walls are built of brickwork, and the sills, quoins, and copings, of a hard Belgian limestone somewhat resembling granite in appearance. The bottom of the lock-chambers, and the aprons, are pitched with basalt laid upon fascines. The gates pointing to the North Sea, or sea gates, are made of iron; the gates pointing inwards are made of wood. The employment of iron for the sea gates, and the introduction of a third pair of sea gates, were due to the natural desire of the Dutch authorities to omit no precautions to secure the country against the inroad of the sea. The Dutch regard iron as a more reliable material for lock-gates than wood; but engineers are not agreed upon this point, as the rapid corrosion of iron by salt water is regarded by some as impairing the advantages they possess in situations not exposed to the sea.

The dam shutting off Lake Y from the Zuider Zee has been constructed across the lake, about two miles to the east of Amsterdam, and is 4462 feet in length. The clay and sand, of which the dam is composed, were deposited on the top of huge fascine mattresses, about $2\frac{1}{2}$ feet thick, laid right across the dam in order to diminish the amount of sinking of the dam in the soft silty bottom of the lake (Plate 2, Fig. 1). At each side of the dam fascine-work dams were raised up to low-water level, and clay and sand were deposited between them. The greatest bottom width of the dam is 147 feet, and its top width is 13 feet. Stone pitching protects the upper portions of the slopes of the dam.

A circular cofferdam was constructed in Lake Y on the line of the dam, at a distance of about 380 feet from the northern shore of the lake, which has been already described in Chapter V (Plate 2, Fig. 3).

The Zuider Zee locks were built inside this cofferdam, which had an internal diameter of 525 feet. Three locks have been constructed at this extremity of the canal, to pro-

vide for the considerable local trade of small vessels between Amsterdam and the ports on the Zuider Zee. The central lock is 315 feet long and 60 feet wide, and the locks on each side are each 238 feet long and 47 feet wide. These locks are similar in construction to the North Sea locks, and like them are each provided with three pairs of iron sea gates, and two pairs of wooden canal gates. There are four sluiceways at the Zuider Zee locks, each furnished with three pairs of gates: one of the sluiceways is on the south side of the locks, it is 34 feet in width, and, like the one at the other end of the canal, serves for letting the water out of the canal when the tide is low; the other three, each 13 feet wide, are placed on the northern side of the locks and form the outlets for the water pumped from the canal, they have brick inverts at the bottom. These works rest on a foundation of bearing piles; and the foundations of the lock walls and sills are enclosed by sheet piling.

The construction of the canal has enabled upwards of 13,000 acres of land, formerly covered by the waters of Wijker Meer and Lake Y, to be drained and reclaimed (Plate 11, Fig. 1). This land has been divided into eight districts, or polders as they are locally called, each served by separate pumps which lift the drainage waters into the canal. The whole of the pumping machinery for lifting the water out of the canal is situated at the Zuider Zee locks, being placed over the three small sluiceways, and consists of three centrifugal pumps, each capable of discharging 24,000 cubic feet per minute with a lift of 7 feet 2½ inches.

The harbour, which had to be constructed at the North Sea entrance to the canal for the purpose of maintaining a deep channel through the shallow sandy beach, is enclosed by two breakwaters stretching out from the shore, each of them about a mile in length (Plate 11, Fig. 7). The harbour has an area of about 250 acres; and a deep channel, 738 feet wide, has been dredged through its centre. Different methods were

tried for building the breakwaters on the quicksand which formed the foundation. A staging of screw piles was first erected for laying the concrete blocks of which the piers are composed; but the sea, scouring away the sand from the piles, brought down the staging. An overhanging crane, travelling on the breakwater, was next tried for laying the blocks in advance of the completed work, but this method proved unsatisfactory. Finally, the plan of depositing a mass of rubble stone forming a broad foundation for the breakwater, and building up the blocks in horizontal courses on the top of the mound, was adopted with success (Plate 11, Figs. 5 and 6). The mound was made only about $3\frac{1}{4}$ feet thick, but about three times the width of the base of the pier, thus affording a wide bearing for the breakwater on the soft foundation. The sea excavated a trench at the sides of the mound when it was first deposited, which became filled up with the loose material from the mound falling into it; and, after the mound had assumed a stable slope at the sides, by being exposed for about a year to the action of the waves, the pier of concrete blocks was built upon it. The concrete blocks, varying in weight from 6 to 12 tons, were laid by means of large overhanging cranes termed 'Titans,' one crane being placed on each breakwater. A number of concrete blocks, weighing from 10 to 20 tons, were deposited at random along the base of the sea side of the outer portion of each pier to protect it from the sea, and assumed eventually a slope of $1\frac{1}{2}$ to 1 under the action of the waves (Plate 11, Fig. 6).

The total quantity of material excavated in forming the canal amounted to 21,000,000 cubic yards, of which 5,232,000 cubic yards were dredged from the harbour.

The total cost of the works amounted to about £2,590,000; but the whole expenditure on the undertaking reached nearly £3,000,000; from this outlay, however, should be deducted the amount obtained by the sale of the reclaimed lands which realised about £70 an acre. Sir John Hawkshaw was the

consulting engineer, and Messrs. Henry Lee and Son contractors for the whole of the works.

Three swing-bridges cross the canal; two are railway bridges, and one is a roadway bridge. These bridges are all built with two symmetrical arms, and supported on a central pivot resting on a pier placed at the foot of one of the side slopes of the canal; so that one of the arms stretches across the central portion of the canal, and the other over one of the slopes, the other slope being spanned by a fixed girder.

A large and rapidly increasing traffic passes through the canal, and the great benefit conferred by its construction upon Amsterdam is fully established.

Full details of this interesting and important work are given in a paper, by Mr. Harrison Hayter, read at the Institution of Civil Engineers in 1880[1].

Though the success of the undertaking as an engineering work is complete, lapse of time alone can indicate what effects the projection of piers on the sandy shore of the North Sea may produce, and whether any changes will occur which may render the maintenance of depth at the entrance difficult and costly in the future. Moles have had to be formed on each side of the canal where it enters the harbour, in order to prevent the sand from the sloping beach in the harbour, and the sand driven along by the wind, from filling up the channel. Dredging is also necessary, to a certain extent, to maintain the depth inside the harbour. The important question, however, is whether the solid piers stretching out from the shore will occasion a progression of the foreshore, as has happened at some ports further to the south on the same coast, as for instance at Calais, Dunkirk, Nieuport, and Ostend. It is quite evident from an inspection of the lines of depths on the chart of the harbour (Plate 11, Fig. 7), and also from the present state of low-water mark as seen on the spot, that a certain amount of progression has already taken place. Time

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. lxii, p. 1.

only can show whether this progression will continue till, at a period more or less remote, the ends of the piers are finally reached. The rate of progression will unquestionably decrease as deeper water is reached; and it is quite possible that the action of the tidal current running across the entrance may limit the progression, besides keeping the front of the entrance free from deposit. Sand blown along the shore is carried over the piers and settles within the shelter of the harbour at the present time; and the quantity of sand thus brought in would increase as the shore line advances, but it can easily be removed by dredging within the sheltered area of the harbour. Indeed the only possible danger, in the future, to the easy maintenance of the entrance to the canal is the advance of the shore; but, even if this should eventually occur to an extent prejudicial to the harbour, it must take a considerable time, and when this emergency arises the harbour could be extended, which, from present appearances, may be safely left to the care of a future generation of engineers.

3. Ship-Canals without Locks, and of World-Wide Importance.

The only existing example of a ship-canal, at one level throughout, without regulating locks, and valuable for all nations, is the Suez Canal: but it may be hoped that before many years have elapsed the Panama Canal will furnish another instance.

Suez Canal. The value of a channel of communication between the Mediterranean and Red Seas, through the Isthmus of Suez, is sufficiently evident from a glance at a map, saving as it does a long circuitous route round the Cape of Good Hope for maritime traffic between Europe and the southern coasts of Asia (Plate 9, Fig. 4). It is certain that the construction of such a channel was not a modern idea, as Herodotus mentions a proposal for cutting

through the isthmus; nor, indeed, can it be considered an entirely modern undertaking, as there is evidence that a water communication, for small vessels, between the two seas was formed and maintained from about 600 B.C. to 800 A.D., but was subsequently allowed to fall into decay.

The idea of reopening a channel of communication appears to have originated with Napoleon I, who, when in possession of Egypt, gave orders, towards the close of last century, for a survey to be made along the line of the ancient route, and an examination of the best available direction for a canal. This project, however, dropped on the evacuation of Egypt by the French. One result, however, of these investigations was the belief that there existed a difference of level of from 25 to 30 feet between the two seas. This erroneous opinion was not rectified till 1847, when a series of levellings were taken across the isthmus, which proved that, practically, there was no difference of level between the two seas at low water, whilst at high water the difference was not more than 4 feet, as the rise of tide is about 1 foot in the Mediterranean and about 6 feet in the Red Sea.

Soon after the coincidence of level was established, M. de Lesseps started a scheme for constructing a large canal, at one uniform level and without any locks, across the isthmus, by the shortest route, which, fortunately, was also the most practicable, as the hollows of Lakes Menzaleh, Ballah, and Timsah, and the Bitter Lakes, lay in that course (Plate 9, Fig. 4). This is the route through which the canal has been successfully excavated (Plate 12, Figs. 1 and 2). Much time was occupied in preliminary discussions and negotiations, and actual operations were not commenced till 1860.

The Canal extends from Port Said, in the Bay of Pelusium, on the Mediterranean, to Suez on the Red Sea, and has a direction nearly due north and south, except through the Bitter Lakes where it diverges to a line pointing north-west and south-east. It is 99 miles long; its width varies, at

the surface of the water, from 196 feet to 328 feet according to the strata through which it is excavated, but the bottom width is 72 feet throughout; its depth is 26 feet (Plate 12, Figs. 3 and 4). The plan (Plate 12, Fig. 1) indicates the route of the canal; and the longitudinal section (Plate 12, Fig. 2) shows the depth of the cuttings at the various points. Along a portion of the Bitter Lakes the surface of the ground was below the level of the bottom of the canal; whilst a deep cutting had to be excavated through El Guisr, the greatest depth being 85 feet to the bottom of the canal. The material excavated consisted of sand or clay, or a mixture of the two, except south of the Bitter Lakes where rocky formations were met with in places.

A harbour has been constructed at Port Said to maintain the channel dredged from the entrance of the canal to deep water in the Mediterranean (Plate 12, Fig. 6). The harbour is formed by two breakwaters, projecting from the shore at a distance apart of 4600 feet and converging to an opening of 2300 feet at the head of the eastern breakwater. The eastern breakwater is 6233 feet long; and the western breakwater is about 9800 feet long, projecting considerably beyond the other so as to prevent the alluvium from the Nile, and sand borne along by the eastward current, filling up the entrance channel. The breakwaters consist of mounds of concrete blocks, weighing 20 tons, deposited at random as shown on the section (Plate 12, Fig. 5).

At Suez the outlet of the canal is protected on the north-west by a solid earthwork embankment, and on the south-east by a mole about 2900 feet long.

An important auxiliary work was the construction of a fresh-water canal from the Nile, near Cairo, to Lake Timsah, and thence in a direction nearly parallel to the line of the main canal as far as Suez (Plate 12, Fig. 1). This canal, about $26\frac{1}{4}$ feet wide at the bottom, $55\frac{3}{4}$ feet wide at the surface of the water, and $6\frac{1}{2}$ feet deep, was rendered neces-

sary by the entire absence of any supply of fresh water along the route of the ship-canal, and from the want of some means of communication by which provisions and materials could be conveyed to the works, situated along a barren scorching desert destitute of all resources of any kind. The supply of water for the canal between Lake Timsah and Port Said was pumped, from Ismaïlia as far as Port Said, through two cast-iron conduits.

The fresh-water canal was also intended to irrigate the land through which it passed; and the portion so irrigated was, according to the terms of the original concession, to become the property of the Suez Canal Company.

The original concession, granted by the Viceroy Mahomet Said Pasha, contained the condition that forced labour should be provided for the work; and during the earlier period of the work the excavations were carried on by about 25,000 native workmen changed every month. In 1863, however, soon after the accession of Ismaïl Pasha, the concession was withdrawn, the supply of forced labour was discontinued, and modifications as to grants of land to the Company introduced. The Company were eventually indemnified for the loss of these and other privileges by a payment from the Viceroy of nearly four million pounds, under an award of Napoleon III; but the withdrawal of forced labour necessitated considerable changes in the conduct of the operations. Labourers from Europe had to be procured, a matter of considerable difficulty for work in that climate; and dredging and other mechanical appliances were adopted as much as possible. Dredging was employed for widening and deepening the canal; and the use of long shoots, already described in Chapter IV, for discharging the dredged material, delivered by the buckets, direct on to the banks, effected a great economy of time and labour (Pl. 1, Fig. 3). Sixty dredging machines were employed on the works, having engines of 35 nominal horse power. The total amount of excavation was about

98,000,000 cubic yards. The canal was opened in 1869. The total cost of the works has been stated by M. de Lesseps to have amounted to a little under £20,000,000; but from this should be deducted the large indemnity, granted in 1864, and other sums paid by the Viceroy, to arrive at the actual financial position of the Company.

The report of M. de Lesseps to the shareholders in 1879 shows that a steady increase was maintained in the traffic through the canal, and in the receipts, from its opening till the year 1877, when the number of vessels reached 1663 in the year, the tonnage amounting to 3,419,000 tons, and the receipts to £1,320,000. These figures fell off slightly in the following year, owing doubtless to the universal depression of trade. The success of the enterprise and its commercial value are now fully recognised.

From a merely engineering point of view the Suez Canal possesses less interest than many far less important works, as, with the exception of the breakwaters at Port Said, no constructive works of any magnitude had to be executed. The canal itself is indeed simply a cutting, partly excavated and partly dredged, from one sea to the other, and is more remarkable for the magnitude of the undertaking, its great cost, and the vast commercial interests involved, than for any peculiar engineering difficulties. The execution of the canal was in reality a question of money and time. These, the real obstacles in the enterprise, were overcome by the great energy and perseverance of M. de Lesseps, and by the excellent organisation displayed in the conduct of the works.

Many persons however, some of them very competent authorities, questioned the expediency, and even the practicability, of the scheme as laid out by M. de Lesseps. It is needless now to go back to the objections urged before the works were commenced, as the facts speak for themselves. Many doubts also were expressed, during the progress of

the works, whether they could be maintained, when completed, at a reasonable cost. It was said that the canal would become a stagnant ditch, the level of the two seas being practically the same; that it would silt up, or that the sand blowing in from the desert would fill it up; that the rapid evaporation in the Bitter Lakes would produce a deposit of salt, and eventually fill them up; and that the entrance at Port Said could not be kept clear of sand. The precise value of these objections could not be ascertained with absolute certainty prior to the completion of the canal; but Sir John Hawkshaw, in a Report to the Viceroy, in 1863[1], and Sir William Denison, in a paper on 'The Suez Canal[2],' in 1867, expressed the opinion that there would be no special difficulty in maintaining the canal. Sufficient time, however, has now elapsed since the opening of the canal to judge how far these adverse anticipations have been borne out by the results of experience.

A series of very careful observations, taken since 1872, of the currents and variations of level along the canal and at its outlets, indicate that, owing to the prevalence of north and north-westerly winds from May till October, the level of the Mediterranean Sea is raised, and that of the Red Sea lowered, causing a difference of level, in September, of 1 foot 4 inches, which produces a current from the Mediterranean to the Red Sea though suffering interruptions from the tides. The direction of the current is reversed by the prevalence of southerly winds in the winter, the level of the Red Sea in January being one foot higher than that of the Mediterranean. It is estimated that the volume of water thus alternately poured from one sea into the other amounts annually to about fourteen thousand million cubic feet. The rate of the current between Port Said and Lake Timsah varies from

[1] Suez Canal. Report of John Hawkshaw, F.R.S., to the Egyptian Government.

[2] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxvi, p. 442.

6 inches to 2 feet per second, and between Suez and the Bitter Lakes it varies from 2 feet to 4 feet 3 inches per second. There is therefore no fear of the canal becoming stagnant, even if such a condition would be of any consequence, unless it tended to affect the health of the passengers in the vessels passing through.

The canal, not being a river bringing down the rainfall of a hilly district charged with detritus, is in no danger of silting up, unless its banks fell in and filled up the bottom under the action of a rapid current. The sand from the desert does not appear to interfere much with the maintenance of the canal; though, undoubtedly, the depth of the canal would be gradually reduced if it was entirely neglected, in such a situation, for a number of years. The dredging required for maintaining its depth, in 1878, amounted to 990,000 cubic yards throughout the whole length of the canal, exclusive of its entrances.

As regards the deposit of salt, which it was prophesied would take place in the Bitter Lakes, experience has shown that the amount of salt which previously existed in the dried-up basin of the lakes has actually decreased since the opening of the canal, owing to the flow of water through them. In the first six years after the lakes were filled the banks of salt were reduced to the extent of seventy-eight and a half million cubic yards, increasing the depth of water in the lakes.

The only objection which appears to have had a valid foundation is that which relates to the difficulty of keeping open the Mediterranean entrance of the canal, and even M. de Lesseps acknowledges that he has only quite recently been able to settle this last point satisfactorily.

The western jetty at Port Said, as it advanced into the sea, arrested the littoral sand-bearing current travelling in an easterly direction, and now diverts it towards the head of the breakwater which it passes in a north-easterly direction

(Plate 12, Fig. 6). The checking of the current produced a deposit of some of the sediment with which it was charged, and consequently a progression of the foreshore in the angle between the outer side of the breakwater and the shore. Moreover, when the breakwater was first formed, the interstices between the blocks allowed the passage of some of the sand or silt through the mound, which settled under the shelter of the breakwater along its inner side. Deposits from the diverted littoral current, and from the sea after westerly gales, form to the north and north-east of the western jetty, extending out to about 1100 yards from the front of the jetty: these deposits, however, are easily removed by dredging. Though a certain amount of deposit does take place beyond these limits, it is very light and is removed periodically by the action of the sea alone. According to the latest reports of M. de Lesseps, deduced from a careful examination of recent soundings and a comparison with former surveys, the western jetty has merely produced a modification of the coast line within a very limited area, and a state of equilibrium has been reached, so that no apprehension need be entertained that the shore will progress to a degree likely to affect the depth of water at the end of the jetty. Even if M. de Lesseps takes too hopeful a view of the case, it is clear that the progression of the shore to the west of the harbour must have already become very slow, and that the maintenance of the outlet at Port Said is assured for a long period. Dredging will of course be needed regularly for maintaining the deep-water channel in the harbour; 580,000 cubic yards were dredged from Port Said harbour for this purpose in 1878, and 40,000 cubic yards had to be dredged for keeping the basins at Port Said clear.

Panama Canal. It is interesting to note that as early as the year 1520 Johannes Schoener made a globe, still in existence in the public library of Nuremberg, with a line drawn across the Isthmus of Panama, as if to indicate that,

in his opinion, there should be a means of communication at that place between the Atlantic and Pacific Oceans.

Various routes have been proposed from time to time for accomplishing this object (Plate 9, Fig. 5). The route preferred by American explorers was through the lake of Nicaragua and the San Juan river, which is known by the name of the Nicaragua route. This route, however, would require twenty-one locks, harbours would have to be formed at each end, and its length would be 180 miles.

The Panama route, following approximately the line of the Panama Railway, is 47 miles long. A tide-level canal can be constructed from Colon to Panama, in open cutting throughout, with good harbours at both ends.

Another line for a canal, explored and proposed by Mr. Kelly, an American, who for many years has devoted much attention to the subject, is known as the San Blas route. This route would possess the advantage of being only 30 miles in length, and for 10 miles of its course the river Bayano could be utilised; locks also would be dispensed with. Unfortunately, however, the canal would have to traverse a tunnel at least seven miles long; and, though a good site for a harbour could be obtained on the Atlantic side, the harbour accommodation on the side of the Pacific Ocean would be bad.

The scheme furthest to the south is the Atrato route, proposed by Captain Selfridge. By this route it would be proposed to follow the river Atrato, from its mouth in the Gulf of Uraba on the Atlantic, for a distance of 149 miles; and then to traverse the remainder of the isthmus by a canal along the valley of the river Napipi, a distance of 31 miles. Thus, though this route would have a total length of 180 miles, only 31 miles of canal would have to be constructed, which would derive its supply from the rivers Atrato and Napipi. The water-level of the canal at the point of its departure from the river Atrato would be 30 feet above the mean level

of the Pacific Ocean, and the descent would be accomplished by two locks placed close to the outlet of the canal. It would also be necessary to provide a tide-lock at the extreme end. A tunnel, $5\frac{1}{2}$ miles in length, would have to be excavated for the passage of the canal across a high ridge.

At an International Congress, held in Paris in May 1879, for the purpose of considering the subject, these and one or two other schemes were propounded and discussed[1]. The Nicaragua scheme was considered unadvisable, on account of its great length, the number of locks which would be required, and its passing through a region subject to earthquakes which might endanger the stability of the works; though, on the other hand, the district possesses the advantages of a fairly dry climate, and a good supply of labour and materials.

The San Blas scheme was rejected by the Congress, in consequence of the long tunnel required, and the difficulty of forming a good harbour on the side of the Pacific Ocean.

As regards the Atrato route, besides its great length, it was considered that the heavy floods of the river Atrato would offer serious obstacles to safe navigation, and it was doubted whether a sufficient depth could be obtained at the mouth of the river without a very large expenditure. Moreover, the locality is not favourable for the construction of a large work, as it is the most rainy portion of the isthmus, the population is scanty, and there is an absence of materials with the exception of wood.

After mature deliberation, the Congress decided, by a large majority, that the Panama route was the best. This route had been surveyed by MM. Wyse and Reclus, at the suggestion of M. de Lesseps, after they had abandoned other routes as impracticable, and it was brought forward at the Congress by these gentlemen. At the close of the Congress, M. de Lesseps was asked to be the leader of

[1] Congrès International d'Études du Canal Interocéanique. 1879.

an enterprise for constructing a canal along the Panama route. Fresh surveys and borings were made in 1879–80; and M. de Lesseps, accompanied by some engineers, inspected the proposed route. On his return he expressed the opinion, that the construction of a ship-canal across the Isthmus of Panama presents fewer difficulties than the Suez Canal, owing to the more favourable climate of the isthmus, the supply of labour and materials, and the experience gained in the previous work.

The site selected is where the ridge of high land running along the isthmus is the lowest. The line starts from the Bay of Limon on the Atlantic, and after following the valley of the river Chagres as far as Matachin, it enters the valley of the river Obispo, and cutting across the Cordilleras through the Culebra pass, it goes along the valley of the Grande river, and finally reaches the Pacific Ocean, near Panama, opposite the island of Perico. The direction of the proposed canal is approximately from north-north-west to south-south-east (Plate 10, Fig. 2). The canal is designed to be in open cutting throughout, though at the highest part of the pass the cutting will have a depth of nearly 300 feet (Plate 10, Fig. 2, Section). The width of the canal at the bottom is to be 72 feet, as in the Suez Canal, except in the deep cutting; and the depth of water will be from 26 to 29 feet. For a distance of 15½ miles, through the Culebra cutting, which is in rock, the bottom width will be 78¾ feet, with side slopes of 1 in 4¼, and the depth of water 29½ feet. The amount of excavation required is estimated at one hundred million cubic yards, nearly half that quantity being rock.

As there is a rise of tide of from 7½ inches to 1 foot 7 inches in the Bay of Limon, and from 8 feet to 21¼ feet at Panama, a tide-lock will be provided at the Panama end to secure the canal against excessive tidal fluctuations; but with this exception the canal will be open from end to end.

The Bay of Panama is so well protected by nature that no

harbour works will be needed at the outlet of the canal into the Pacific Ocean. The entrance, however, into the Bay of Limon is exposed to northerly winds, and will have to be protected by a breakwater one mile and a quarter in length.

The chief difficulty anticipated in the work is the control of the large and sudden floods which periodically occur on the river Chagres; but it is proposed to convey the flood waters into an artificial reservoir, to be formed by constructing a dam, 130 feet in height, across a suitable part of the valley. This reservoir has been designed to have a capacity larger than the volume of any flood that can possibly come down from the river Chagres and its tributaries; and the water will be let off to the sea through artificial channels.

The cost of the work, estimated at the prices fixed by the Paris Congress, would amount to about £33,700,000; but, as an extreme price was put upon earthwork wherever the nature of the material had not been accurately ascertained, M. de Lesseps considers that the actual cost will prove considerably less, and consequently has fixed the capital of the company he has formed at £24,000,000. The contractors, MM. Couvreux and Hersent, estimate the total cost at only £20,480,000, exclusive of the general charges of the Company and the cost of the tide-lock at Panama. It is considered that the works can be completed in eight years.

A canal along the Nicaragua route has at the same time been sanctioned by the Nicaraguan Government, and a concession granted to an American Company; so that there is every prospect that before long the Isthmus of Panama will cease to be a barrier between the Atlantic and Pacific Oceans.

M. de Lesseps has insisted strongly on the necessity of making the Panama Canal of one level throughout, without the encumbrance of locks, following the same view which he urged in promoting the Suez Canal, that a canal intended for the traffic of all nations is of comparatively little value unless its course is entirely unimpeded. Undoubtedly locks

delay the passage of vessels through a canal, and, moreover, limit the capacity for traffic of a canal; so it may be regarded as a most fortunate circumstance that, as regards the two routes of world-wide importance, an open channel proved the simplest plan for the Suez Canal, and a channel with only one tide-lock appears feasible for the Panama Canal.

4. Ship-Canals from Inland Ports to the Sea, and Lateral Ship-Canals in place of River Navigation.

It is unnecessary to dwell at any length on the canals comprised in this last class, as they closely resemble in their general features one or other of the canals already described; it will therefore suffice to draw attention to the conditions under which they are executed.

Gloucester and Berkeley Canal. The city of Gloucester has direct access to the sea by the River Severn and the Bristol Channel; but for some miles below Gloucester the course of the river is circuitous, and the rapid flow of the tides renders the navigation at that part both difficult and dangerous for barges and small vessels. Accordingly an Act was obtained, in 1793, for connecting Gloucester by a direct ship-canal with the estuary below. After much delay this canal, known as the Gloucester and Berkeley Canal, was completed by Telford in 1827. It is 16½ miles long, and level throughout, commencing at Gloucester, and rejoining the Severn, under the shelter of a projecting headland called Sharpness Point, in the parish of Berkeley, where a tide-lock maintains the water in the canal at a uniform level. The canal has a bottom width of from 13 to 20 feet, a width at the surface of the water of from 80 to 100 feet and wider at passing places, and a depth of 18 feet.

Canals from Bruges to the sea. Bruges was one of the most important commercial cities in Europe from the

thirteenth to the fifteenth century; but, like Rye and Sandwich, its trade was gradually injured by the silting up of its communication with the sea. Its harbour, at Damme on the Zwyn, was formerly so large that, in 1230, Philip Augustus of France fought a battle in it against the combined English and Flemish fleets. The Zwyn was, however, even then gradually silting up, as within a century from that time the canal from Bruges to Damme had to be prolonged to Ecluse; and by the close of the fifteenth century the Zwyn was so much silted up as to bar the passage to large vessels. Bruges, however, did not relinquish its maritime position without a struggle. A canal was made from Bruges to Ostend in 1622, and another was made to Nieuport in 1640 and prolonged to Dunkirk; but on the surrender of Dunkirk to France, in 1646, Ostend became the best available deep-water outlet, and the Bruges-Ostend Canal was enlarged in 1664. During the occupation of Belgium by the French, at the commencement of this century, an attempt was made, by order of Napoleon I, to open up again the original route to the sea by reconstructing a canal from Bruges to Ecluse, with a prolongation to the estuary of the Scheldt near Breskens, but the fall of Napoleon put a stop to the work; the canal, however, was opened as far as Ecluse in 1818. The silting up of the Zwyn has, however, increased since that period to such an extent, that the Dutch have placed a dam across it and reclaimed the land; so that the old route from Bruges to the sea has now been finally closed.

The construction of a new ship-canal from Bruges to Heyst on the North Sea has recently been proposed by M. de Maere-Limnander. The distance is only $7\frac{1}{2}$ miles; and the proposed dimensions of the canal are, a bottom width of 66 feet, a width at the water line of 203 feet, and a depth of 23 feet. The design includes a harbour at Heyst, formed by two breakwaters, somewhat similar to Ymuiden Harbour at the North Sea entrance of the Amsterdam Canal, and enclosing

an area of about 150 acres. Heyst has been selected for the outlet of the Bruges Canal, as, whilst it is not far from the nearest point of the sea-coast to Bruges, it is the spot where a depth of 23 feet at low water is obtainable at a shorter distance from the shore than elsewhere along the coast. It is hoped that the Belgian Government may take up the scheme, as supplying a national want of a deep-water harbour for trade and for refuge; as Ostend is unfavourably situated for depth of water, and the estuary of the Scheldt is in Dutch territory.

Ghent-Terneuzen Canal. Though Ghent is situated on the Scheldt, the river there is so small, and its course to the sea is so circuitous, that various endeavours have been made to obtain a better route for its commerce. The first effort was made in 1251, when a canal was excavated in the silted up bed of the Lieve, with an outlet at Damme the port of Bruges. Later on a more direct course was formed by the construction of the Sas Canal, opening at Sas-de-Gand into the Braeckman an arm of the sea, which was completed in 1562. This route was closed, in 1648, by the treaty of Munster. A canal from Ghent to Bruges was completed in 1758; but this route, like the earlier one to Damme, placed Ghent at a great disadvantage, in comparison to its ancient rival Bruges, as regarded communication with the sea. In 1827 the Sas Canal, having been deprived of its original outlet by the silting up of the Braeckman, was provided with a new outlet by the construction of a canal to Terneuzen (Plate 15, Fig. 4).

The distance from Ghent to Terneuzen by this canal is only 21 miles, whereas by the Scheldt it is 105 miles. This canal has, however, proved inadequate for the larger class of vessels introduced since its construction. It is now being straightened, and much enlarged. It is being formed with a bottom width of $55\frac{3}{4}$ feet, a width at the water line of $173\frac{1}{2}$ feet, and a depth of from 19 feet 10 inches to 22 feet 5 inches.

As the deep-water channel of the Scheldt estuary passes close to Terneuzen there will be no difficulty in forming and maintaining a sufficient depth at the outlet.

Lateral Canals. Sometimes a river has such fluctuations in its flow, or such abrupt variations in its fall, that its canalisation, so as to be suitable for safe and continuous navigation, is difficult, or occasionally impossible. Thus the Rhone, which in its lower course has a flood discharge twenty-eight times greater than its low-water flow, cannot be properly regulated so as to have a depth and an even flow suitable for navigation; and, according to M. Krantz, a proper water communication between Lyons and the sea would have to be provided by a lateral canal. A lateral canal has been constructed, below Toulouse, in prolongation of the Languedoc Canal, as far as Castets, a distance of 120 miles, in preference to the improvement of the Garonne (Plate 9, Fig. 1).

The Welland Canal is a notable instance of the formation of a lateral canal, where the natural water communication of the Niagara river, between Lakes Erie and Ontario, is rendered impassable by the insuperable barrier of the falls of Niagara (Plate 10, Fig. 3).

Lateral canals have been proposed at various places for avoiding the obstacle to navigation presented by a shallow channel, or a bar, at the mouth of a river. Thus lateral ship-canals were advocated to take the place of the natural channels through the deltas of the Mississippi and the Danube, and instead of the River Liffey between Dublin and the sea. Fortunately, for reasons which will appear in the sequel, these proposals were not carried out. The Saint Louis Canal, however, is an instance where such a measure has been adopted with successful results (Plate 20, Fig. 1). The silt brought down by the Rhone is carried along the coast towards the west by the prevailing easterly winds: but, as the winds produce only a surface current, a considerable portion of the sand is deposited at the river mouth, and forms a bar.

This bar has been avoided by the construction of the Saint Louis Canal which, issuing from the Rhone above the bar, enters the Mediterranean in the Bay of Foz to the east of the outlet of the Rhone, beyond the range of the alluvial current which tends to travel in the opposite direction. This canal is a little over two miles long, 200 feet wide at the level of low water, and 19½ feet deep. A lateral canal had been previously formed, starting from the Rhone at Arles (Plate 20, Fig. 1), and entering the Mediterranean at Bouc further to the east, with the same object; but it proved too small when the introduction of steam altered the whole conditions of river navigation.

The canal of Mahmoudieh affords a communication between the Nile and the Mediterranean, which enables vessels to escape the shallow channels of the delta of the Nile. The canal also of San Carlos, from Amposta on the Ebro to the Bay of Alfaques, enables the trade of the Ebro to avoid the delta of that river.

CHAPTER XIII.

FLOODS OF RIVERS, AND THE MEANS OF MITIGATING THEIR EFFECTS.

Fen Rivers; Drainage of the Fens. Exclusion of Tide by Sluices. Cause of Floods and Methods of Prevention. Inundation of Middle Level by the Sea, and Repair of Breach. *Floods in River Valleys.* Effects of Canalisation. Obstruction produced by Mills. Causes of Increase of Floods. Prevention of Summer Floods. Estimation of Flood Discharge. *Protection against Floods.* Embankment of Rivers, its Advantages and Disadvantages. Enlargement of Existing Channels. Removal of Obstacles to Discharge: Straight Cuts. Erroneous Opinions as to Oblique Weirs and Level Reaches improving the Discharge of Rivers. Flood Storage Reservoirs. System of Procedure for Mitigating Floods. Warnings of Floods. Rating for Drainage Improvements.

In the opening chapter it was pointed out that rivers are the natural channels by which rainfall is conveyed to the sea. Whatever changes may be introduced into a river for the sake of navigation, this primary office of rivers, to which they owe their existence, cannot be neglected. The methods by which a river may be improved for navigation above its estuary or the tidal portion of its course have been already described; and they mainly consist in rendering a river as like a canal as possible, consistently with the constantly varying flow which it has to discharge.

There is one class of rivers, more particularly, which holds a sort of intermediate position between canals and rivers. These are the rivers which flow through flat, low-lying districts; they are very artificial in their character, and, though originally they were natural rivers, they now resemble in many respects mere drainage canals, such as are met with

throughout Holland, and present few indications of their former condition.

Fen Rivers.

Drainage of the Fens. The Fen rivers of England are instances of the class referred to above; they formerly meandered through marshy flats which were covered with water at high tide or in flood time. When these lands were reclaimed, by shutting them off from the sea by banks, it became necessary to embank the rivers also, in order that the tides and fresh-water floods passing along them might not inundate the lands. Moreover, as the natural fall of these rivers was very small, it was necessary to straighten their course, and frequently to widen and deepen their channels, to enable them to carry off the additional water discharged into them from the reclaimed lands. As the water in the river frequently rises above the surface of these lands, their drainage can be only partially effected by gravitation, through flap doors or sluices which close against the river as its waters rise; and the remainder of the drainage water has to be raised and discharged into the river by pumping, being led to the pumps by numerous straight cuts or drains.

Exclusion of Tide by erection of Sluices. It was very natural that the persons interested in the reclamation of the Fens, a tract of country so much resembling Holland, should have summoned Dutch engineers to their aid, who had special experience in the reclamation, protection, and drainage of land. By the advice of Vermuyden and others, sluices were erected at different times across the rivers and drains for the purpose of excluding the tide. Thus sluices exist at Denver on the Ouse, at St. Germains on the Middle Level Drain, at Boston on the Witham, at the outlets of the Forty Foot, Maud Foster, and Hobhole Drains, and at other places. A pair of gates pointing towards the sea constitute the essential element of these sluices; the gates close when the tide rises above the

level of the water inside, and open again as soon as the tide has fallen below the inner level. The course thus adopted was naturally recommended by the Dutch, who have an instinctive anxiety to keep out the sea as far as possible, as it is their natural enemy in their own country.

Injury to Outfalls. The advantages of preventing the tide coming up the rivers and drains are, that the banks on each side do not require to be so strongly made, or raised so high, as if they had to withstand the inroad of the sea; also that the exclusion of salt water enables the river water to be utilised in irrigating the adjacent lands in dry weather. The Dutch engineers, however, in providing for the safety of the lands from the incursions of the sea, neglected all consideration of the outfalls of the Fen rivers which, being deprived to a great extent of the original flux and reflux of the tide through them, began to silt up, and thus became less adequate to provide a sufficient outlet at low tide for the drainage water.

Necessity for Catchwater Drains. Another point of great importance appears to have been overlooked in the earlier efforts of draining the Fen lands. The basins of the Fen rivers do not consist of uniformly low-lying lands at one dead level, as in Holland; but portions are, in comparison, at a considerably higher level. The fall that can be obtained from the drainage of these upper districts is ample; but if the rainfall of these high lands is allowed to descend into the Fen lands this fall is lost; and the discharge of the drainage waters becomes as difficult as if the whole basin was at one uniform level, with the additional disadvantage that the waters from the high lands, coming down more rapidly, reach the river sooner than if the surface was flat; and under these conditions a more sudden accumulation of water has to be discharged.

As the fall of the Fen rivers is small, it is necessary to provide ample channels for the discharge of a given volume

of water. If, however, the drainage of the higher lands is intercepted by catchwater drains before it reaches the low-lying lands, these drains can be given a sufficient fall to discharge readily the drainage of the high lands into the river at a lower part of its course. This plan, advocated on several occasions by Mr. Rennie, and subsequently by his son Sir John Rennie, both relieves the Fen lands below of a considerable quantity of water, and also reduces the volume which the upper river has to convey, enabling a smaller channel to carry the drainage waters, or leaving a more ample margin for the discharge of floods.

Causes of Floods in the Fens. The floods which have occurred at various times in the Fens may be mainly attributed to the above causes; namely, defective outfalls, and the descent of the drainage of the high lands into the Fens.

Other causes, however, contribute to the occurrence of floods. One is that the Fen country, in being drained and cultivated, tends to subside somewhat, being consolidated by becoming dry and by ploughing. This subsidence amounts to two or three feet in some places[1]. It of course renders a more efficient drainage necessary in order to lower the standing water-level, whilst the power of draining into the river by gravitation alone becomes less; and therefore, unless additional pumping power is provided, the drainage water is more liable to back up behind the banks when the river is in flood, and, overflowing the drains, to inundate the land.

The more thorough drainage of a river basin brings down the rainfall more rapidly into the main river which, accordingly, is filled in a shorter period, and has less time wherein to discharge the rainfall of the land lying nearest to it before the arrival of the water from the lands farther off.

In some of the Fen rivers also, the water is maintained at a certain level for the sake of navigation, which, though useful in dry seasons for irrigation, if there is a sufficient supply, yet

[1] History of the Fens of South Lincolnshire. W. H. Wheeler.

in flood time, by hindering the free discharge, and by preventing the emptying of the channel before the flood comes down, leads to the heightening of the flood level.

The division of authority and of interests which exists, even in such a well regulated district as the Fens, where the removal of the drainage water is of paramount importance, both leads to a less careful supervision of the banks than is necessary, and also hinders the adoption of comprehensive schemes of improvement. The inhabitants of each separate district are unwilling to aid in the execution of special works, which would benefit their lands as well as others, unless these works are carried out within their own district.

Floods in the Fens may accordingly be traced to deficiencies in the outfalls, the inadequate supply of catchwater drains, the subsidence of the land, the extension of drainage, the conflicting interests of navigation, the insufficient inspection and maintenance of the side embankments, and the want of co-operation in carrying out adequate schemes of improvement.

Methods of improving the Drainage of the Fens. The means by which the defects in the outfalls might be remedied belongs to the subject of tidal river improvement, which will be treated of in the next chapter. Straightening, deepening, and widening the river channel is the natural method of securing a better discharge, which helps to keep down the river floods within the limits of safety, and reduces the ordinary water-level of the river, thus facilitating improvements in drainage. This method has been resorted to in numerous instances in the Fen country. Thus, on the river Witham, a new cut was made early in the present century from Lincoln to Bardney, a distance of about $7\frac{1}{2}$ miles, for diverting the navigation, leaving the river perfectly free for drainage; and the river channel between Bardney and the Grand Sluice close to Boston, 23 miles in length, was deepened and enlarged in 1868. The side banks are at the same

time strengthened and raised by the material excavated from the channel; so that not only is the ordinary capacity of discharge of the channel improved, but the floods can rise higher than before without endangering or overtopping the banks.

The Fen rivers have been supplemented by numerous drains, which collect the drainage of the districts situated at a distance from the main river, and eventually discharge their contents into the main river. These drains in fact form artificial tributaries, laid out so as to follow the best and straightest course for the discharge of the waters of the districts they drain. Thus the Middle Level Drain, collecting the drainage of the Middle Level district, discharges into the Ouse above the Eau Brink Cut; and the drainage of the Witham basin is aided by the Forty Foot, Maud Foster, and Hobhole drains, which drain respectively the Black Sluice district, the West and Wildmore Fens, and the East Fen, and discharge into the estuary of the Witham at different points below Boston (Plate 13, Fig. 6). The small amount of fall attainable renders it important, that, besides adopting the straightest possible course for the cuts and drains, the fall should be made as regular as possible throughout, so that every portion may have its full share of fall which, in most cases, is small enough. It is only in dealing with the very small falls of the Fen rivers, sometimes amounting to only from four to six inches in a mile, that the value of a small increase of fall, for reducing the section needed for a channel to discharge a definite volume, is fully realised.

The discharge of the lowest drains into the main river, or into larger drains, has frequently to be accomplished by pumping. Formerly windmills were used for raising the water; but steam power has been substituted now, as the former method, though cheap, was irregular and inadequate. It is evident that the whole drainage of a district can be effected by pumping, as in the case of the Haarlem Meer and Lake Y

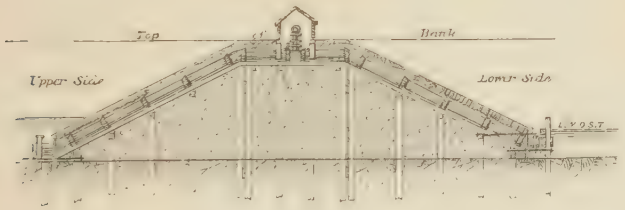
reclamations incidentally alluded to in the description of the Amsterdam Ship-Canal. About 35,000 acres of the Fourth District of the river Witham have been drained by pumping since 1870; and whereas, previously, much of this land was frequently submerged, it has been kept free from water by the pumps in the most rainy seasons.

The combined effects of improved outfalls, a complete system of catchwater drains, the enlargement and straightening of channels, the strengthening and raising of embankments, and the removal of obstructions, supplemented by pumping where the fall is deficient, could be made adequate for the discharge of any fresh-water floods that might occur; but the benefit gained might not always justify the expense. Thus in Holland, in very rainy seasons, the water sometimes lies on the land, whereas increased pumping power is all that is required for its removal. It might, in like manner, be advisable in the Fen country to arrange for relieving the banks, during excessive floods, by letting the water escape quietly on to the lands through sluices in the banks, rather than take the risk of a bank breaking, sooner or later, when the rush of water through the breach produces far more injury than the mere covering of a greater area with water.

Inundation of the Middle Level by the Sea. Though every precaution is taken against the inroad of the sea, occasional breaches have been formed by the sea in the solid reclamation banks during storms accompanied by very high tides; and, as recently as 1862, the St. Germains' Sluice, forming the outlet of the Middle Level Drain into the tidal portion of the Ouse, gave way, admitting the tidal waters into the drain. The tide rushed in and out of the drain with great velocity, and went a distance of twenty miles up the drain. Though every attempt was made to secure the banks of the drain against the unexpected pressure and scour, a breach was at last made, about four miles above the sluice, inundating about 6000 acres of land. In this emergency the Commis-

sioners applied for advice to Sir John Hawkshaw, under whose direction the works for excluding the tide were carried out[1]. A cofferdam, consisting of two rows of piles with clay filling between, was erected across the drain a short distance above the fallen sluice; and the central portion of the cofferdam was closed against the tide by letting down wooden panels, at slack tide, between two pairs of guide piles, and filling up the interior of the dam with clay in advance of the tide as it rose. Sheeting piles were subsequently driven in front of the panels on each side of the dam. The cofferdam was firmly strutted and tied together, and sloping banks were formed on each side of it. Directly the tide was excluded from the drain, the breach in the bank was easily repaired.

Siphons on Middle Level Drain. To provide for the discharge of the drainage of the district, which had originally passed through the St. Germains' Sluice but had now no outlet, an old disused channel and sluice outlet into the Ouse was cleaned out and re-opened, and sixteen cast-iron siphons



Siphons on Middle Level Drain.

Fig. 18.

were erected over the cofferdam for conveying the drainage water from the drain into the Ouse. The siphons were each 150 feet in length, and 3 feet 6 inches internal diameter. The upper part of the siphon was laid horizontally on the top of the cofferdam, and an arm extended down on each side, resting on an inclined framework at an inclination of 2 to 1; the top

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxii, p. 497.

was 21 feet 6 inches above the extremities of the arms which were always under water. The siphons were furnished with valves at each extremity, so that they could be set in action, either by exhausting the air by means of an air-pump connected with the top, or by filling them with water. The upper or inlet valve was a flap of teak working inwards; and the lower or outlet valve was of cast-iron, working outwards and fitted with a balance weight.

New Middle Level Sluice. These siphons served all the purposes of the customary sluice, with the advantage that the safety of the district was not dependent on a single pair of gates, and that each siphon could be removed for repairs singly, without interfering with the action of the rest. It was accordingly proposed, when they were put up, that they should form a permanent substitute for a sluice. It was, however, found that the siphons were not of sufficient capacity to let off always the full flood discharge of the drain; and it was feared that an extraordinary and long continued flood might so far gain upon the siphons as to overtop the dam. Accordingly, a sluice of the ordinary type has been recently erected in a new cut parallel to the siphons. The new Middle Level Sluice has three openings, each 17 feet wide, which are each closed by two pairs of gates pointing seawards, so as to prevent any chance of a recurrence of the catastrophe; and the sills are laid 16 feet below the highest flood level.

Necessity for further Improvement Works in the Fens. A great deal of skill has been employed, and large sums of money expended, in the Fen country, in improving the drainage and affording protection from floods. Much, however, still remains to be accomplished before the district can be considered to have been placed in a perfectly satisfactory condition, as floods still not unfrequently occur in very rainy winters. For instance, in 1877, on the Witham, lands were flooded above and in the neighbourhood of Lincoln, and a breach was formed in one of the banks, a few miles below

the city, which caused considerable damage to the adjacent lands. Concerted action, or the fusion of the various authorities, who have now separate jurisdiction within each river basin, into one active efficient body, is necessary before much additional progress can be made.

Floods in River Valleys.

Little has been done by nature for the Fen rivers, and much has been accomplished by art. When, however, the case of river valleys in more favoured districts is considered, the contrast they present to the Fen rivers is remarkable—here so much has been provided by nature, that in most cases nothing has been done by art. In fact, frequently, the natural means of drainage have been impeded rather than assisted; and, whilst improved methods of drainage on the high lands have discharged the rainfall more rapidly into the river, no attempt has been made to keep its channel clear.

Effects of the Canalisation of Rivers on Floods. The channel formed by nature is usually amply sufficient for the ordinary flow, but quite inadequate, especially along flat plains, to hold the flood waters. When a river is utilised for navigation, or for mills, the natural fall is interfered with, and diminished in each reach to the extent of the fall at the lock or mill below. Generally, however, in the case of navigation channels this loss of fall is compensated for by increasing the depth, and sometimes the width of the channel. The deepening for rendering a river navigable is specially advantageous for the flow of the river, as variations in depth, and particularly long shallows, retard the current considerably. In rendering a river navigable it is not the interest of the promoters to reduce the flood level; they have only to endeavour not to raise it. Their object is to secure a sufficient depth of water at all times; and if they were merely to increase the sectional area of the river, they would so promote its free discharge that the river in dry seasons would run nearly dry.

They accordingly erect weirs across the channel, as before mentioned, which retain the water in dry weather; and in flood time the discharge, though impeded by the weirs, is promoted by the deepening of the river; so that in a well-designed scheme for the canalisation of a river neither injury nor benefit is done to the riparian proprietors. The canalisation of a river, however, possesses the disadvantage, as regards floods, that it permanently raises the water-level of the river, and prevents the riparian proprietors from being able to improve the discharge, and lower the water-level, by merely removing the principal shoals and natural obstructions, as can be done when a river exists in its natural state. It also hinders full advantage being taken of any warning of a coming flood, by preventing the opening of all sluices beforehand, as the navigable depth has to be maintained.

Injurious effects of Mills across Rivers. Mills alone on a river, without canalisation, offer much greater impediments to its free discharge, as no improvements are effected in the river except close to the mill; and it is the miller's interest to ensure an ample supply of water above his mill by keeping the river as full as possible. Even when the river is in flood, the flood sluices of a mill are frequently kept closed, or only partially opened, as the miller has to keep the upper water at a very high level in order to maintain a sufficient head for working his mill when the tail water rises below. Thus the flood is increased all up the valley of the mill-stream, each miller keeping up the water as much as possible, and thus raising the tail water of his neighbour above, who to secure himself does precisely the same thing. The only result to a small river of possessing a good fall, and consequently a better natural discharge, is that more mills are established across it; so that it is reduced to the same state, as regards liability to floods, as rivers less favourably circumstanced by nature.

Causes of Increase of Floods. Any draining of land or cleaning out of ditches and watercourses, which enables the

rainfall to flow more rapidly into a river, tends to increase the floods of the river. Moreover, detritus brought down from mountain slopes by a torrent, and earth washed from the banks, settle in a river bed when the flow of the river is checked, as happens when its fall is reduced. This deposit, and the growth of weeds at the bottom of a river bed, gradually raise the bed, and reduce the capacity of the channel. Accordingly, in many instances, the river channel, which was originally inadequate to carry off the flood waters, is gradually reduced in section, at the same time that a greater volume of water is being poured into it than formerly within a given period. Floods do, periodically, scour out the channel which otherwise would be filled up, but their action is irregular, and the full effect is not produced till the flood is passing off.

Winter Floods. In many cases it would be almost impracticable, or at any rate far too costly, to provide and maintain a channel adequate to carry off the maximum flood discharge without any flooding of the adjacent lands; but fortunately, in general, winter floods are not injurious when flowing gently over the ground. Moreover, the waters flowing over the adjacent meadows in the winter, not only afford a relief to the river, but also convey some of the sedimentary matter from the river channel, which it would tend to fill up, on to the land which it helps to fertilise.

Summer Floods. Summer floods, on the contrary, are most injurious to the farmer; they ruin his growing crops, injure and sometimes carry off his hay, and render the second grass crops unpalatable to cattle. The volume of summer floods is, however, considerably less than that of winter floods, as was pointed out in Chapter I. Summer floods, therefore, could and should be confined to the river channel, except in very exceptionally wet seasons, which, occurring at distant intervals, would entail less pecuniary loss than the cost of sufficiently large works to provide against such unusual floods.

Data required relating to the Extent and Discharge of Floods Before preparing any scheme for the better discharge of the flood waters of a river, it is very important to study the physical characteristics of its valley, as referred to in Chapter I; and also to ascertain, as far as practicable, what the maxima discharges in times of flood amount to at different periods of the year, at what periods the floods generally occur, and to what extent they are injurious.

The gauging of the flood discharge of a river is somewhat difficult, as the waters extend, in many places, over a wide area, and the flow is liable to vary as the river in rising finds additional outlets below. Frequently no sufficiently accurate data, or records of observations sufficiently widespread and extending over a long enough period, exist to indicate what the flood discharge of a river may amount to at various points and at different seasons of the year. The only method that can be resorted to under such circumstances is to ascertain the maximum rainfall over the area of the basin in a given time, and then, after making deductions for evaporation, absorption, infiltration, and any other causes of loss, to assume that the rest of the rainfall, reckoned as a depth in inches and decimals of an inch over the basin, must be discharged by the river. The result thus arrived at should be checked by as many direct gaugings of the stream as time and circumstances may permit.

A river has to discharge an increased volume of water as it proceeds downwards in its course to the sea, each tributary furnishing an additional supply, and a certain amount of water draining in all along its banks direct from the land, and from ditches and springs, till at length, just before it joins another river or falls into the sea, it has to discharge the whole of the available rainfall of its basin. The amount of water a river channel can convey varies with its sectional area and its fall: whilst, however, the volume to be discharged becomes greater in the lower parts of a river, the fall of the

river is reduced, so that a larger increase in the size of the channel has to be provided than would correspond with the increase in volume, though fortunately this is somewhat compensated for by the reduction of friction in a larger channel.

Protection against Floods.

There are three general methods by which protection may be afforded against floods: (1) The erection of embankments along each side of a river; (2) Improvement of the existing river channel by widening, deepening, and straightening it; (3) Construction of reservoirs for impounding the surplus flood waters.

The method of disposing of flood waters by pumping has been already referred to, and it is only resorted to where the fall is deficient, the land very valuable, and the outlet ample. The system of reducing the floods of mountain torrents by planting trees and promoting the growth of grass on the denuded slopes was mentioned in Chapter I, and has only a very restricted application.

Embankment of Rivers. The method of protecting land from floods by erecting embankments along each side of a river possesses several advantages. It provides an enlarged section above for the discharge of the flood waters, and leaves the existing water-levels unaltered. Moreover, by placing the embankments back a certain distance from the banks, the available section of the river can be enlarged to any extent, at the mere cost of the land and of the embankments. Many rivers have been controlled in this manner, as for instance the Po and the Theiss, which, possessing only a small fall, in flowing across extensive tracts of level plains, have been systematically embanked. Where low-lying lands border the tidal portion of a river, or where a river flows through flat marshy districts such as the Fens, embankments afford the only available means of preventing inundation. Thus the tidal waters are kept out by banks from the low-

lying lands bordering the estuary of the Thames; and the river Witham is embanked from Lincoln to the sea.

Sometimes low banks are constructed merely high enough to retain moderate floods, being submerged on the occurrence of great floods.

When, however, high embankments are formed for the purpose of securing the surrounding country from inundation, they must be made strong enough to resist the full pressure of water, perfectly watertight, and high enough to be safe from any chance of being overtopped by a flood, for if the river rises above them they are soon destroyed by the rush of water. This was the cause of the Szegedin disaster in 1879. The river Theiss on descending to the plains of Hungary has a very small fall, amounting to from 6 to 9 inches per mile above Szegedin, and to only 1·2 inches between Szegedin and its junction with the Danube. In consequence the plains through which the river winds were frequently flooded, and the extent of country covered by these floods was 6000 square miles. Of this area, 4200 square miles have been protected by the regulation of 740 miles in length of river. The works of improvement, however, have been stopped since 1867; and the necessary works for counteracting the gradual rise of the flood level, owing to the silting up of the river bed, having been neglected, the waters of the Theiss rose above the protecting embankments, in 1879, and, forming a breach, destroyed a portion of the town of Szegedin and inundated two hundred square miles of country.

The valley of the Po is frequently devastated by floods, though protected by the embankment of the river, nineteen considerable floods having occurred between 1800 and 1876. The worst flood appears to have taken place in October 1872, when thirty-three breaches were formed in the embankments; and the water was not drawn entirely off the inundated lands till the following April. It is a subject of dispute, whether

the level of the bed of the Po has been gradually raised, or merely the level of its floods.

It is evident that an embanked river is liable to accumulate in its channel the silt which ordinarily would be deposited, in flood time, over the adjacent plains. As, however, the result of observations tends to prove that this has not occurred in the bed of the Po, it is probable that the channel has been cleared out by the rush occasioned by the bursting of the banks, and possibly also by the improved scour of the regulated current. The progressive rise of the floods, which gives cause to much anxiety, must under these conditions be attributed to improved drainage or the removal of forests.

The system of longitudinal embankments, or levees as they are called in America, has been resorted to for a long time for the protection of low-lying lands in the valley of the Mississippi with successful results; and it is proposed to extend them in a continuous line down the river from the mouth of the Ohio. Though breaches do occur in them during floods, they are mainly attributed to the employment of defective materials; and, whilst their value in reclaiming inundated land is acknowledged, it is stated that they benefit navigation by marking the channel and forming a kind of quay for local traffic in flood time.

Embankments have to be most efficiently constructed and maintained, and very carefully watched, to prove satisfactory safeguards against floods. Moreover, the bursting of an embankment is productive of far more disastrous consequences than even the periodical overflowing of a river, partly owing to the imagined security enjoyed, and partly to the great rush of water which ensues on the bursting of the bank, carrying all before it. For these reasons low banks, liable to be submerged by the highest floods, are frequently preferred.

In some cases the embankments have to be periodically raised, owing to the raising of the river bed by the deposit of alluvium. Some rivers in Japan are remarkable instances

of this. These rivers bring down large quantities of detritus from the mountains, which they deposit in their beds, whilst traversing plains on their way to the sea. The rivers have been confined within embankments for a long period, and the embankments have been gradually raised to keep pace with the rising of the river beds, so that, at the present time, the level of some of these rivers is as much as forty feet above the level of the plains over which they flow. Accordingly, in constructing railways along these districts, it has been found occasionally easier to make a tunnel under the river bed than to raise the railway over the river[1]. These high embankments require constant attention, and not unfrequently give way, causing destruction to life and property. This is no doubt an extreme instance, but it shows to what lengths the system of embanking may be carried in certain cases.

The Commission appointed by the Italian Government, in 1872, to consider the best means of preventing the inundations of the Po, decided that it was unadvisable to endeavour any longer to confine the floods within the river channel by adding to the height of the embankments, as such a course tended to aggravate the dangers which it was designed to prevent.

Enlargement of existing Channels, and Straight Cuts. The method of promoting a better discharge in a river by deepening and widening it, is liable to entail a greater cost, in the first instance, than the system of embanking. It necessitates the lowering of the sills of sluices and locks on navigable rivers, and the erection of additional sluices or movable weirs to maintain the summer level of the river, in the improved channel, at its original height. The cost, however, of maintenance is less than with embankments; and the method possesses the decided advantage of being unattended by the disasters which the rush of water through a broken

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. lvi, p. 10.

bank entails. This method, moreover, lowers the flood level of a river; whereas embankments raise it, as manifested by the relief which the upper river experiences when a breach is formed below. Also, by following this course, the river channel need only be made sufficiently large to be capable of discharging summer floods. The surplus waters of the comparatively harmless though larger winter floods may be allowed to flow over the adjacent lands, and to deposit on them the alluvium with which they are charged. Low banks may with advantage be added at the sides, to restrict the range of exceptional summer floods where the fall is very small, or where for other reasons it may be difficult to provide an adequate channel.

Whether a river is embanked, or its channel enlarged, or a judicious combination of the two systems is adopted, it is important that all obstacles to its flow, such as weeds, fallen trees, fish-traps, and weirs with high sills, should be removed. Movable weirs might also be advantageously substituted for existing overfall and inadequate draw-door weirs, as they enable the level of the water above them to be more efficiently regulated than is possible with overfall weirs, and, when lowered, they leave the channel entirely unobstructed, and consequently capable of giving a free discharge in time of flood. The waterway also under old bridges should be increased as much as possible; for these structures, with their wide piers and narrow openings, frequently present a considerable obstruction to the flow.

Straight cuts may also sometimes be advantageously made to reduce the length of the channel, and consequently increase the fall. These cuts are most advantageous where the fall is very slight; in other circumstances they must be adopted with caution, as the variation they introduce in the flow, and the deviation they produce in the currents, tend to neutralise their good effect. Cut-offs, as they are called in America, have been tried on the Mississippi; but they

are not regarded with much favour, as, though they reduce considerably the length of the channel in the large bends of the river, the labour involved is large, they develop currents unfavourable to navigation, and the changes they produce in the velocity of the flow tend to form shoals below.

Oblique solid weirs, and the impounding of water in level reaches, have been imagined by some engineers to have a favourable effect in assisting the discharge of flood waters.

With regard to the effect of solid weirs, it is evident that nothing which obstructs a channel can improve the discharge through that channel. The error arose from the effects produced by the improvement of a river, and by the removal of shoals, being attributed to the weirs which were simultaneously erected to retain the water for navigation.

Level reaches have been assumed to be advantageous to the discharge of floods, because water, poured into the upper end of a level reach which is quite full, discharges an almost equal volume of water at the lower end more quickly, than if the water had to traverse the whole length of the reach when empty, and to encounter the friction against the river bed. The discharge, however, thus produced, is merely due to the transmission of force through the particles of the water; just as, in a row of balls in contact, the shock of an impinging ball is transmitted to the foremost in the row, which starts off upon a course in advance of the position which the ball producing the motion would have occupied if it had passed on unchecked. As, moreover, such a row of balls gradually assumes a more backward position if a series of balls successively impinge upon it, for these balls accumulate in the rear whilst the foremost balls move on; so the continued discharge of water into the upper part of a level reach raises the level of the water in the upper part, and renders it less capable of admitting the flow from above. Moreover, it is clear that a freer discharge would be promoted from

above if the reach was empty; and the aforesaid condition of a full reach would be eventually arrived at, with the advantage, in this case, of a volume of water sufficient to fill the reach having been discharged from above. It is evident that importance attaches, not to the fulness, but to the emptiness of a reach when a flood comes down, and to its capacity for receiving an additional supply.

Flood Storage Reservoirs. It has been frequently suggested that reservoir basins should be formed in river valleys for receiving the surplus flood waters which the river is incapable of discharging, so that the surplus waters may be retained from flooding the lands below, and then allowed to escape quietly when the flood has subsided. Reservoirs constructed at Pinay and La Roche, in the valley of the Loire, early in the last century, are stated to have proved of considerable service in mitigating floods on that river; and an extension of the system was proposed some years ago for providing against floods in that valley. A dam was actually commenced at Furens with this object in view; but before the work was completed, the reservoir, formed by the dam in the valley d'Enfer, was utilised for supplying the town of St. Etienne with water: it, however, also serves for preserving the town from inundation. It has also been suggested that the flood discharge of the river Yonne in France should be regulated by the formation of reservoirs. Both the Loire and the Yonne, however, are torrential rivers flowing over impermeable strata, and with a rapid fall in their upper portions. It might be possible to find sites in the valleys of these rivers, or their tributaries, where short high dams might retain a large volume of water; but unless the water thus stored up could be utilised, it is doubtful whether, even on this class of river, the results would justify the expenditure.

In most cases, however, the establishment of reservoirs for the control of floods is open to very serious objections. Many

river valleys, as for instance those of the Thames, the Seine, and the Mississippi, are not suitable for the formation of storage reservoirs; and in such cases the cost of making adequate reservoirs would be far greater than the value of any benefits they could confer. Also, supposing proper reservoirs to have been formed, they would be unable to cope with a rapid succession of floods, as when once filled they would be unavailable for the succeeding floods. Reservoirs are not likely to become economically applicable for dealing with floods, unless their cost can be reduced by favourable local conditions, and by their being also employed for supplying irrigation canals, or for the supply of water to towns. Natural reservoirs may occasionally be obtained, where barren tracts of low-lying land are capable of improvement by being flooded by a river and receiving a deposit of alluvium. The tendency, however, of agricultural improvements lies generally in an opposite direction, namely, to reclaim districts formerly serving as natural reservoirs, which has led to a rise in the level of the floods in the adjacent valleys, and has increased the damage they effect.

An interesting example of this may be seen in the Upper Thames basin, a few miles from Oxford. The river Ray, a tributary of the river Cherwell which enters the Thames at Oxford, flows through a low marshy district called Otmoor. In order to improve this district, which was constantly flooded by the river, a new channel was cut for the Ray near the higher lands, it was embanked with the material excavated, and the river diverted from Otmoor into this channel. When, however, the floods came down, the channel proved insufficient to convey the waters, and, the old reservoir being shut off, the river rose, flooded the lands above the new cut, and threatened to burst through the embankments. It was found necessary, accordingly, to relieve the flood waters, by making a passage for them through the embankment and allowing them to flow over their old reservoir area. Natural reservoirs

of this kind form valuable outlets for flood waters, and should be retained for this purpose, unless the value of the land, when reclaimed, would pay for an adequate compensating enlargement of the channel.

System of procedure in Drainage Improvement Works. In improving a river for the purpose of diminishing damage from floods, it is most important that a comprehensive scheme should be adopted for the whole river, and the works commenced at the lower end. If the upper portion of a river is improved without any works being carried out below, the result is that, the water being discharged more freely from above, the flooding of the lands below is increased; so that whilst the upper section of the river valley is relieved, the lower section is proportionately injured. Also banks constructed by a landowner, on one side of a river, to protect his lands from floods, divert the surplus water, that originally flowed over his land, on to the land of his neighbour on the opposite bank.

The outfall of a river must also be included in the general scheme, unless it has previously been improved for the sake of navigation, as an ample and unobstructed outlet is of primary importance for securing the proper discharge of the drainage of the district.

Warnings of Floods. The system of giving warnings of approaching floods, established along the Seine and its tributaries by M. Belgrand, in 1854, by the aid of rainfall returns and observations of the rise of the upper portion of a river and its tributaries, has proved of great value in preserving life and property. It has been brought to such a state of perfection on the Seine, that during a great flood in 1876, M. Belgrand was able to predict, three days beforehand, the maximum height of the flood at Paris to within half an inch. On the same occasion the flood, though greater than any since 1807, did little injury below Paris, owing to the timely warning given of its approach. For, in one place an embankment

was heightened above the predicted flood level; and the inhabitants of the low districts removed with their cattle and goods to places of safety.

The same system has been adopted on the Loire, and might be applied, with great advantage, to many large rivers; though, in some cases, owing to complications arising from the variations in rainfall and stratification, the results could not be predicted with such absolute accuracy.

Rating for Drainage Improvements. The great difficulty in the way of carrying out any comprehensive scheme, in ordinary river valleys, for the prevention of floods, consists, not so much in the want of co-operation between the landed proprietors, as in the absence of any means of raising adequate funds for executing the necessary works. In France, and in many cases in America, river works are conducted by the Government at the expense of the State, so that their cost only forms an item in the general taxation, and is borne by the nation at large. In Holland, in the Fen districts, and in large flat valleys like the Mississippi, where considerable tracts of low-lying land are exposed to floods, it is not difficult to assess the rates needed for drainage improvements and works of protection; and the rates, being levied over an extensive area, do not constitute an excessive burden.

In the case, however, of ordinary river valleys, the flooded area is so small in relation to the works that require to be undertaken to restore and improve the neglected and artificial channel, that the necessary rate, if imposed solely on the lands liable to be flooded, and those situated only a few feet above flood level, would bear such a large proportion to the value of the land, as to preclude the notion of executing thoroughly efficient works, even for the prevention of summer floods.

It has been frequently asserted by interested persons, with some appearance of justice, that only those lands should be rated which would derive direct benefit from the improvement

of the channel; and also that the uplands have the right of long established usage to discharge their drainage waters down on to the lowlands. Upon these principles, however, all towns, formerly discharging their sewage and refuse into a river, would have a right to continue the practice to the detriment of those towns situated lower down on the same river; but the legislature in England has deprived towns of these powers, in the interests of the public. In like manner, the opinion has been gradually gaining ground, since more enlightened views have been brought to bear on the subject, that the whole basin of a river should bear some share of the burden of making the river channels adequate for the efficient drainage of the district. For the uplands, as well as the lowlands, drain into the main river, and aid in swelling the floods, more especially since the extension of subsoil drainage which conveys the rainfall more rapidly into the principal channels.

It is now considered that no landowner should be free to discharge, as rapidly as possible, the drainage water off his land, without affording any compensation for the injuries thereby inflicted on his less fortunately situated neighbours; but that all should bear some share in the advancement of the general good in drainage as in other matters. The Rivers Conservancy and Floods Prevention Bill, which for two sessions has occupied the attention of Parliament, accordingly proposes, that the rateable area for drainage improvement should be coextensive with the area embraced within the watershed; but that as the lower lands would be specially benefited by the works, they should bear a much heavier rate. A comparatively trifling rate, levied over the whole area of a river basin, would furnish the necessary funds for converting the rivers into adequately efficient channels of drainage to prevent the frequent occurrence of summer floods. The prosperity and healthiness of the country would by this means be enhanced; the productiveness of the low-lying lands largely increased, and constantly recurring losses from floods avoided.

The Conservancy Bill, without compelling the inhabitants of a river valley to improve the drainage of their district, will enable Boards to be formed for this purpose in each drainage area, with adequate powers of levying rates, and having control over the whole of the valley.

CHAPTER XIV.

IMPROVEMENT OF TIDAL RIVERS.

Bars; Causes of Formation. Influence of Tidal Flow, and Fresh Water Discharge. Effect of Sluice Gates. Effect of Tidal Flow on the Outlet. Influence of the Form of Tidal Channels. General Principles of Improvement. Improvement of the Mouths of Small Tidal Rivers. *River Liffey*: Works at the Outlet; Effect on Channel across the Bar. *River Wear*: Piers at Mouth; Results. *River Yare*: Description of Outlet Channel; Piers at Mouth. *River Adour*: Bar; Jetties at Mouth. *Outfalls of the Fen Rivers*: Deterioration; Straight Cuts on the Nene and Ouse; Training Works and New Cut on the Witham; Training Works on the Welland; Necessity for further Works at the Outfalls. General Remarks on Methods of Improvement.

THE value of a river for navigation is dependent on the depth which can be attained at the shallowest point of its navigable channel. Unfortunately the action of natural causes generally forms a bank, or bar, in front of the mouth of a river; so that the shallowest part of the channel occurs just where it is most difficult to improve it.

Bars. A bar is a ridge, or shoal, across the navigable channel, at the mouth of a river, over which there is a less depth of water than in the adjacent portions of the channel. The formation of bars may be attributed to two principal causes:

(1) The tendency of the sea, or of waves driven along the shore by the prevailing winds, or of littoral currents, to heap up the beach in a continuous line along the shore, and close up the outlet of the river, which is only partially prevented by the scour of the tidal ebb and flow, and the discharge of the inland waters.

(2) The deposit of material, brought down by a river, when the velocity of the river is checked on entering the sea.

The formation of bars at the mouths of tidal rivers is mainly due to the first cause; whilst the action of the second cause is most clearly manifested at the deltas of rivers flowing into tideless seas. Thus the bar at the mouth of the river Adour (Plate 16, Fig 5) is formed by the waves which, rolling in from the Bay of Biscay, in a south-easterly direction, bring sand into the entrance, as is clearly shown by the bar being higher directly after a storm. The operation of the second cause is well illustrated at the shallow mouths of the Nile and the Danube (Plate 20, Fig 5).

Occasionally the effects of littoral currents and prevailing winds, when acting obliquely to the coast line, are so powerful that they actually choke up the natural mouth of a river, and force it to find a vent in another place after having gained strength by the accumulation of its pent-up waters. This result has occurred with the river Yare at Great Yarmouth, and the river Adur at Shoreham. The Yare formed six different outlets in succession before the present one was secured in 1559, and its mouth is $2\frac{3}{4}$ miles to the south of its ancient outlet (Fig. 20, p. 242).

The effect of river deposit in the formation of bars is less clearly marked in proportion as the tidal range up a river is greater. For a tidal river has a tendency to deposit its sediment along the whole length of its tidal course, as slack water occurs successively at every point along this portion of the river at the turn of the tide; and a portion of the sediment is only gradually brought down to the mouth of the river by the action of the upland waters which gradually escape into the sea.

The formation of a bar is affected by various local conditions, such as the force and direction of the prevalent winds and littoral currents; the slope of the beach and the depth of the sea in the neighbourhood of the outlet; the

velocity and duration of the tidal ebb and flow; the amount of the fresh-water discharge, and the proportion of sediment which it brings down. The form also of the estuary of a river exercises an important influence on the depths at its mouth. Thus rivers opening out into large estuaries, such as the Severn and the Scheldt (Plate 15. Fig. 4), are free from bars; and rivers gradually widening out as they approach the sea are not impeded by bars, though they sometimes have sandbanks between which the river flows through good channels to the sea, as for instance the Thames and the Humber.

The word 'bar' is, however, in reality merely a relative term, which is applied to a shoal at the outer end of the entrance channel to a port when the shoal is prejudicial to navigation; as the navigable channels of even those rivers which are said to be free from bars vary considerably in depth (Plate 15. Fig. 5. and Plate 16. Fig. 2), and have shallower places which would be called bars if the depth of water over them was not amply sufficient for the vessels navigating the river.

Shoals also exist whenever the current of a river has its velocity abruptly checked, owing to a reduction of scouring force and the deposit of material previously held in suspension. A shoal is a sort of inner bar situated higher up a river than the bar commonly so called.

The object of all tidal river improvement is to remove bars and shoals, to prevent their reforming, and to improve the navigable depth.

Influence of Tidal Flow and Fresh-water Discharge in a River. Before proceeding to describe the past and present condition of some of the navigable tidal rivers, and the works which have been carried out on them, it will be advisable to examine briefly the influence which the tidal and upland waters exert on a tidal river channel, and the general principles upon which tidal river improvements are based.

Considering, in the first place, the effect of the tidal ebb

and flow in a simple creek, unaffected by any fresh-water discharge; it is well known that, if the waves or littoral currents charge the flood tide with sand, the creek will gradually silt up, as, though the ebb tide brings out again a large portion of the material brought in by the flood, a portion of the sediment, deposited at slack water at the turn of the flood tide, is left behind. This result is commonly accounted for by saying that the flood is stronger than the ebb; but it would be more strictly correct to say that the flood tide, which is impelled up a creek by the velocity of the tidal current and the difference in head between the water in the sea and in the creek, has its force diminished by the inert mass of water previously in the creek, and by friction against the sides of the creek, which also reduce the force when reversed on the ebb. Accordingly, the force of the ebb in the creek is less than the force of the flood by the sum of the retarding forces acting during both the flood and ebb tides. The silting up is also promoted by the sediment, when once deposited, being less easily removed than when held in suspension, and by the smaller velocity of the tidal current at the bottom.

Proceeding now to the more complicated case of tidal rivers; in addition to the ordinary tidal flow there is a volume of fresh water flowing down to the sea. During the flood tide the whole of this water is penned back; and the whole of the discharge of the river, during a period of twelve hours, has to escape during the ebb. In this case, accordingly, the ebb tide is reinforced by the fresh water; so that a tidal river is much more capable of maintaining itself than a mere creek. The influence, indeed, of river floods in maintaining the depth of a tidal river is clearly proved by the fact, that bars at the mouths of rivers are frequently raised during dry summer weather and scoured away again when the winter floods come down. The water discharged from the non-tidal section of a river does not arrive at the sea in the course of

a single ebb tide when the tidal section is long, but it proceeds by successive stages, and its influence in reinforcing the ebb is precisely the same.

Whereas in a creek the flood tide has a preponderating influence, and accumulates silt; in a river the balance is reversed, and the descending current predominates. The fresh waters, indeed, bring down their share of sediment which is deposited when the current is checked; but, on the whole, a sort of equilibrium is reached, and the silt, which accumulates in the channel when the fresh-water discharge is small, is carried on towards the sea in time of flood. If a state of equilibrium was not attained, the river would either continue deepening its channel till its scouring power was sufficiently reduced to produce no further effect, or its channel would gradually silt up till the concentrated current was able to maintain the diminished channel.

Slow changes are, indeed, taking place in most estuaries of rivers; in some parts the coast is wearing away, and in others the shore is advancing, producing corresponding alterations in the outlets. The most rapid and unexpected changes, however, occur when the natural state of equilibrium is disturbed by artificial works, which therefore should be undertaken with great caution, and must be based upon sound principles.

Effect of Sluice Gates across Tidal Rivers. It has sometimes been assumed that, as the tide when flowing into bays or creeks tends to fill them up gradually with sand or silt, therefore the tidal ebb and flow in rivers is injurious, and that rivers would be in a better condition if the tide was excluded from them, as the sedimentary matter brought in by the flood tide would be thus shut out, and not be deposited in the river channel. This opinion, however, is not borne out by experience. For instance, the harbour of Rye, at the mouth of the river Rother, was injured by reclamations, and by the erection of Scott's sluice, which, stopping the

flux and reflux of the tide up and down the river, caused a rapid accumulation of silt in the channel below the sluice; and the subsequent destruction of the sluice produced an improvement in the outlet.

It is related by the French engineer M. Cordier, that the harbours of Dunkirk and Gravelines suffered injury from a similar cause[1]. M. Bouniceau gives an interesting account of the deterioration of the channel of the river Vire, in Vays Bay, by the erection of tidal gates across the river near Isigny, and of its restoration to its original condition, by giving free admission again to the tide on the removal of the gates[2]. Denver Sluice, placed across the Ouse, soon occasioned a silting up of the river below; and the Grand Sluice across the Witham, just above Boston, restricting the tidal flow which formerly extended up to Lincoln, thirty miles higher up the river, permanently injured Boston as a port (Plate 13, Fig. 6).

A very brief consideration of the subject shows that a deterioration of the channel below is the inevitable result of the stoppage of the tidal flow, when the flood tide is charged with silt. When the tide flows up a river it possesses a definite velocity which enables it to hold in suspension the sand and silt which it carries up with it; but on encountering any barrier which prevents it from flowing further up, its motion is stopped, and it simply rises vertically against the barrier, and deposits, during the long period of almost absolute slack water thus produced, nearly all the sand and silt which it brought up. Thus the silt is sometimes heaped up as high as ten feet against the gates of the Grand Sluice at Boston in the summer, and is only removed by the winter floods. Moreover, the effect of such a barrier is not confined to the portion of the river in its immediate vicinity, for, though the tidal flow is absolutely arrested only at the barrier, it

[1] De la navigation intérieure du Département du Nord, M. Cordier, p. 105.

[2] Étude sur la navigation des rivières à marées. M. Bouniceau, p. 62.

is affected for a long distance down a river in proportion to the proximity to the barrier. The exclusion of the tidal waters from a portion of the channel is, accordingly, more or less injurious to the whole regimen of the river below; and the value of the mere tidal ebb and flow in maintaining a channel is made evident from the results which follow on the exclusion of the tide.

Effect of Tidal Flow on the Outlet of a River. It has been seen that the outlet of a river is the most critical point of the whole channel, and that, owing to the diminution in velocity which the current generally experiences at that part, it is the place where a shoal, or bar, is most likely to form. Slack water is the period when deposit mainly occurs, and hence it is of great importance to reduce this period as much as possible. It is clear that in a simple creek, the longer and larger the creek is inside, the better will the outlet of the creek be maintained, as the period of slack water will be reduced by the tide taking a longer period to flow up and down the creek, and a stronger current will be produced at the outlet. The deterioration of the outlet channels of the harbours of Calais and Ostend, as the shallow tide-covered areas within the harbours became reclaimed, furnishes examples of the great injury that may be effected in an outlet by the simple reduction of the tidal volume passing and repassing through the entrance. As far, therefore, as the outlet alone of a river channel is concerned, it will be better maintained in proportion to the tidal capacity of the river above it.

Influence of the Form of Tidal Channels. The amount of tidal water which enters a river, and the range of the tidal influence, which have been shown to be of such importance towards the maintenance of a river, depend upon the form and depth at the mouth, the rise of the tide, the fall of the river bed, and the general configuration of the river channel. The mouth of a river should have such a form as to admit, easily, at every tide, the full volume of water that the tidal

channel of the river is capable of receiving; any contraction at the mouth prevents the complete filling of the river, and diminishes both the tidal volume entering a river, and the extent of its influence. As the flood tide entering a river has to fill successively the several sections of the river, commencing at the mouth, the sectional area of a river channel may gradually diminish, as it recedes from the sea, in proportion as the tidal volume introduced becomes less. The suitable rate of this reduction depends on the tidal range, and on the fresh-water discharge of a river. This shows why rivers with trumpet, or funnel-shaped, estuaries possess good outlet channels, their form approximating to that which theoretical considerations indicate as the best; moreover, with such a form there are no abrupt changes in the velocity of the currents. It is true that a contraction of the outlet channel improves, for a time at least, the depth in the channel, owing to the increased scour thereby produced; but it interferes with the tidal flow up the river, and thus hinders or prevents the complete filling of the tidal channel; it also causes irregularities in the flow, both above and below the narrowed channel, which promote deposit. Similar prejudicial effects are produced by any contraction or irregularity in the channel of a river above its mouth.

A rapid rise of the bed of a river inland counteracts the effect of the tidal rise at its mouth, and prevents the tide from going far up the river channel: moreover, by producing a rapid fresh-water flow, it causes an antagonism between the fresh-water discharge and the flood tide, which still further limits the range of action of the tide and has a tendency to form a bar.

Though the high-water line is affected by the form of the estuary into which the tide flows, being for instance considerably raised in flowing up the Bristol Channel, so that the tidal range is much greater in the upper part of the estuary of the Severn than at the outlet of the Bristol Chan-

nel, artificial works are not of sufficient magnitude to alter it materially. Every work, however, which improves the tidal flow in a river lowers its low-water line, owing to the escape of the ebb tide being facilitated. As the lowering of the low-water line, unaccompanied by a lowering of the high-water line, indicates the admission of a larger volume of tidal water, and an increased velocity and a more efficient scour of the ebb tide, the amount of lowering of the low-water line of a tidal river may be taken as a sort of measure of the improvement effected (Plates 17, 18, and 19).

In wide estuaries the flood and the ebb tides do not always follow the same channels; this change of channel occasions a long period of slack water in each channel alternately, causing silting up, and also leads to the formation of cross currents which tend to wash silt from the banks into the main channels. In consequence the advantages that might be expected from the comparative absence of conflict between the first of the flood and the last of the ebb are more than neutralised. Experience, moreover, proves that, under such conditions, the channels are much more liable to change their positions, than when the flood and ebb tides are confined to one and the same channel.

General Principles of Improvement. The general principles upon which all schemes of tidal river improvement should be based may be briefly summed up as follows:—

The tidal flow should be admitted as far up a river as possible, and all barriers to its progress removed, so that the period of slack water may be reduced to a minimum. By this means also the area of inevitable deposit is enlarged, and thus the deposit does not unduly shoal the channel when the fresh-water discharge is small; and the volume of tidal water flowing through the outlet is thereby increased.

The fresh-water discharge should not be abstracted, if possible, for supplying canals or for other purposes, but should be directed into the upper end of the main tidal channel, so

that it may have the fullest possible effect in reinforcing the ebb throughout the whole of the tidal course of the river, as the power of the outflowing current to maintain the channel depends upon the additional force thus furnished to the ebb.

The form of the estuary should be regulated so as to enlarge gradually as it approaches the sea, and thus promote regularity of flow without unduly restricting the tidal capacity above the outlet. This may be sometimes accomplished by low training banks which, whilst directing and concentrating the latter half of the ebb, do not materially impede the admission of the flood tide up the estuary. Where the estuary is very wide and irregular, and the main river channel through it is very tortuous and shifting, high embankments may be formed, on each side, widening out towards the sea, and the land behind them reclaimed.

Examples will now be given of the past and present condition of some tidal rivers, with short descriptions of the works executed for their improvement.

Improvement of the Mouths of Small Tidal Rivers.

When rivers are small, and the length of their tidal portion comparatively short, the improvements are mainly confined to increasing the depth of the channel at their outlet, for the benefit of the port situated at their mouth, or only a short distance from it.

Some of the continental harbours on the North Sea coast are situated at the mouths of small rivers, or on creeks into which a certain quantity of land water is discharged. Thus for instance Gravelines harbour, in France, was formed at the mouth of the river Aa, and Nieuport harbour, in Belgium, at the mouth of the river Yser: whilst Calais and Dunkirk harbours were established at the mouths of creeks which were maintained by the tidal flow aided by some fresh-water discharge. The character of river channels has, however, been

almost obliterated in these harbours by successive reclamations and modifications, so that they now more nearly resemble purely artificial harbours, their outlet channels being confined between parallel jetties extending into the sea, and maintained by sluicing and dredging.

Dublin, Sunderland, Great Yarmouth, and Bayonne, on the contrary, are instances of harbours where the original river origin has not been obliterated; and therefore the improvements effected at the mouths of the Liffey, the Wear, the Yare, and the Adour, for the benefit of these harbours, may fitly come under consideration. The Fen rivers too, which by a different management might have become tidal rivers of some importance, have had their tidal flow so restricted as to possess harbours only near their outlets, and they may therefore be included in the same category.

River Liffey.

The port of Dublin is situated near the mouth of the river Liffey, which, after joining the river Dodder, flows into Dublin Bay [1] (Plate 13, Fig. 3). Large quantities of sand are brought into the bay by the sea, and have accumulated on its western shore. The river Liffey flows across these sands, dividing them into two strands, called the North and South Bulls, which are dry at low water.

Improvement Works. In the early part of last century the outlet channel was constantly changing both in depth and direction. Accordingly the improvement of the river was commenced. The upper part of the channel, near Dublin, was rectified, and quays begun; and a jetty of rubble stone was commenced on the southern side of the channel, along the northern limit of the South Bull (Plate 13, Fig. 1). This jetty, called the Great South Wall, was constructed for the purpose of straightening the outlet channel, in order also to protect it in south-westerly gales, and to prevent sand coming

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. lviii, p. 104.

into it from the South Bull. It was completed in 1796, and is about $3\frac{1}{3}$ miles in length.

Besides fulfilling the purposes for which it was primarily undertaken, it somewhat increased the depth of the channel, more especially near the mouth, in consequence of the tidal scour round its head. The channel was also deepened by dredging. Whilst, however, the depth in the river channel and at its outlet had been improved, the depth of the bay in front of the outlet, known as Dublin bar, had remained unaltered. This bar is due to the tendency of the sands to form a continuous strand right across the western shore of the bay, which is only prevented by the tidal scour through the channel aided slightly by the fresh-water discharge of the river. In order to increase the depth over the bar another embankment of rubble stone, called the Great North Wall, was commenced in 1820, starting from the shore some distance to the north of the river channel, and running in a south-easterly direction so as gradually to converge towards the south wall (Plate 13, Fig. 2). The wall, which is about $1\frac{3}{4}$ miles long, was completed in 1825, and it is raised only to half-tide level along its outer part.

Combined Effects of Jetties and Tidal Currents. By the position given to the north wall a large area of strand, covered at high tide, is enclosed in addition to the channel; and the ebbing waters form a concentrated current through the contracted outlet between the ends of the walls, and produce a scour over the bar during the latter half of the ebb. At this period the tide outside the entrance is running towards the east, and carries a portion of the sand, scoured from the bar, on to the North Bull, and the rest into deep water. This sand is not brought back again when the flood tide commences to flow, as the tide still sets towards the east on the northern side of the bay during the earlier part of the flood. During the earlier half of the ebb the current from the harbour escapes over the low part of the north wall. If the

north wall had been raised to high-tide level throughout, the earlier ebb current would have been intensified and directed over the bar. This current, however, would have possessed little scouring effect, the sand it might have carried out would have been brought back by the flowing tide, and its rapid flow would have been prejudicial to navigation near the time of high water. Accordingly, the raising of the outer portion of the north wall would not only have entailed additional cost, but would also probably have proved an injury instead of an advantage.

Dredging has been resorted to for improving the upper part of the channel, and for removing the sand which falls in from the north strand. The tidal capacity of the harbour is being thereby continually improved; and this improvement is aided by the removal of ballast from the north strand.

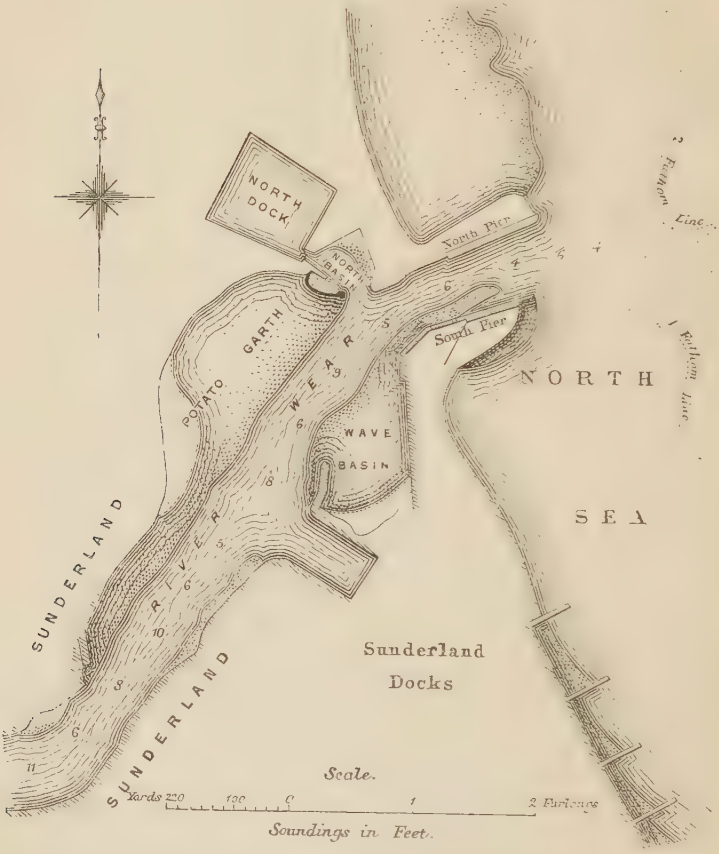
Results of the Works at Outlet. The results of these works have been most satisfactory, as shown by the longitudinal sections of the channel in 1819, 1856, and 1878 (Plate 13, Fig. 4). Ten years after the completion of the north wall, the bar had been lowered 5 feet; and in 1861 the total increase in depth amounted to 7 feet, and reached nearly 10 feet in 1873, giving a depth of 16 feet in the channel across the bar at low-water spring tides. Mr. Griffith, in his interesting Paper on this subject[1], states it as his opinion that, within the next few years, a depth of 18 feet at low water will be attained without any further works.

That such an improvement has been effected on a sandy shore, within a land-locked bay where sand is constantly accumulating, is an evidence of the great value of tidal scour when judiciously directed. Reclamation within the river has been strictly avoided; and the outlet channel appears to be secure from deterioration, by the aid of a moderate amount of dredging, till the gradual accumulation of sand on the North and South Bulls brings the low-water line in front of the jetties, when an extension of these works will be necessary.

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. lviii, p. 119.

River Wear.

The port of Sunderland is situated at the mouth of the river Wear; and, till the extension of the docks to the south



River Wear.

Fig. 19.

rendered another entrance advisable, the river formed the sole approach channel to the port (Fig. 19).

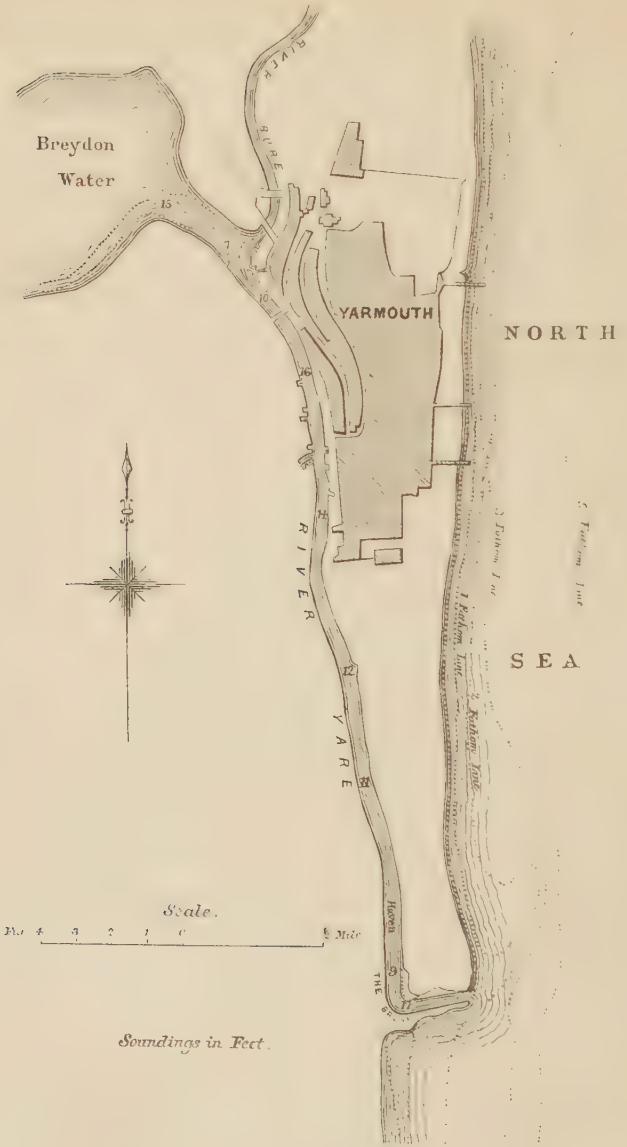
Works at Mouth of River Wear. A pier was commenced on the shore, in 1723, along the south side of the river, to direct its current across the bar at its mouth, which even some years later appears to have been very nearly as high as low-water level[1]. The channel of the river was somewhat improved by dredging and removing shoals ; and any attempts at encroachments on the foreshore for quays or land reclamations were firmly resisted. Occasionally, however, storms drove the sands from the north side into the channel and choked it up. A timber jetty was accordingly erected, in 1786, along the northern side of the channel across the beach ; and the southern pier was extended with timberwork, in order to prevent the inroad of sand and to direct the outgoing current against the bar. These jetties were shortly after strengthened with rubble stone, and eventually rebuilt about 1843. The recess of the Potato Garth, left on the north side, and the setting back of the south pier, when it was rebuilt, furnished tidal receptacles, within the river mouth, which increased the tidal scour between the piers.

Results of Works. By these works the depth over the bar had been increased to 4 feet below low water of ordinary spring tides, and this depth has been maintained. The improvement thus effected in the outfall produced an improvement in the depth of the river above, and altered the tidal flow in the river, making high-water level at Biddick, nine miles above the mouth, the same as at the sea. Though the low-water line on the shore advanced nearly to the end of the piers after their construction, it seems long ago to have reached a state of equilibrium.

River Yare.

The harbour of Yarmouth is formed by the outlet channel of the rivers Yare, Wavency, and Bure (Fig. 20, p. 242). The two first-named rivers flow into a large mere, or shallow lake, called

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. vi, p. 256.



River Yare.

Fig. 20.

Breydon Water, which probably was formerly a creek communicating with the North Sea; and the river Bure joins them at the lower end of the mere. Doubtless, originally, the outlet of these rivers was where the town of Great Yarmouth now stands: but wave-driven sands from the north have turned the river, on issuing out of Breydon Water, in a southerly direction parallel to the coast. The river, having followed this course for about 2¾ miles, makes a sharp bend at a point called the Brush, and flows through a short straight channel into the sea. This outlet was permanently fixed by jetties in 1559. The channel is protected, at its entrance to the sea, by two nearly parallel piers placed about 200 feet apart. The northern pier projects beyond the other, and was made solid to protect the mouth of the river from the sand drifting along the coast from the north.

The outlet of the river is maintained by the inland and tidal waters directed by the piers across the bar: and dredging is carried on to increase the tidal receptacle and deepen the channel. In this instance (as at Shoreham and other places), the formation of a tidal reservoir was effected by the action of the sea along the beach, forcing the river to follow a devious course. The piers have been carried out just far enough to enable the out-going current to act on the bar which is formed by the drift of sand from the north-east. A depth of about 10 feet at low water spring tides has been attained at the mouth of the river; but the rise of tide is small, being 6 feet at springs, and 4½ feet at neaps.

River Adour.

The river Adour forms the entrance channel to the port of Bayonne which is situated a short distance from its mouth (Plate 16, Fig. 5). This river flows into the Bay of Biscay, on the west coast of France, near the angle which this coast makes with the north coast of Spain; its mouth is exposed to the full force of north-westerly storms, which raise a violent sea

upon the coast. The sand is driven by the winds and waves in a south-easterly direction, and is constantly tending to raise a bar at the mouth of the Adour, through which the river has to force a passage.

Jetties at Mouth of River Adour. Rubble mounds were placed, many years ago, along both sides of the outlet channel, to contract the entrance; as it was hoped that by concentrating the out-going current the bar would be swept away. The bar, however, was only carried just beyond the guiding jetties, and formed again in front, where the influence of the jetties ceased, and the current lost its velocity on entering the open sea. Moreover, the contracted entrance prevented the free admission of the tide up the river, so that the rise of tide, which is only 8 feet 2 inches at ordinary spring tides on that part of the coast, was reduced at Bayonne. About twenty years ago parallel jetties were carried out across the bar, at right angles to the shore, in continuation of the rubble mounds. These jetties consist of iron cylinders, with spaces between them, and surrounded at the base by a solid mound which is raised slightly above the level of the beach. The influx of sand from the beach is thus prevented by the solid base; whilst the spaces between the cylinders leave a passage for the littoral currents, with the object of avoiding an advance of the foreshore. Panels, which can be slid down grooves at the sides of the cylinders, enable the spaces between the cylinders to be closed at pleasure; so that the jetties can be made close, to concentrate the ebbing current from the river over the bar, or the panels raised to allow the shore currents to pass through the jetties.

The jetty system adopted at the mouth of the Adour has proved only partially successful; for though the channel over the bar has been stopped from shifting, and its depth increased by about $3\frac{1}{4}$ feet, the bar still exists beyond the outlet, and the jetties have occasioned a progression of the foreshore.

The Outfalls of the Fen Rivers.

The low-lying Fen district is drained by the rivers Witham, Welland, Nene, and Ouse, which flow into the large sandy estuary of the Wash (Plate 13, Fig. 5). The fall of these rivers is very small throughout the lower portions of their course. The methods by which the drainage of the district is led into the rivers, and whereby the discharge of the main rivers has been improved, have been already referred to in the previous Chapter. The outfalls, however, were for a long time entirely neglected, with injurious results both to the drainage and to the ports situated on the tidal portions of the rivers.

The ports of Boston, Spalding, Wisbeach, and King's Lynn, situated respectively on the Witham, Welland, Nene, and Ouse, all suffered from the gradual deterioration of the channels leading to the sea.

Boston Haven, formerly a harbour of some importance, was also injured from other causes. The flux and reflux of the tide on the Witham, above Boston, was stopped by the Grand Sluice, only three-quarters of a mile above the town. This abstraction of tidal flow through the haven, caused silt to deposit in the channel, which is only partially removed by the winter floods of the river. Moreover the drainage waters, which exercise such an important influence in the maintenance of a tidal river, have been to a great extent diverted, so as to flow into the Witham below Boston Haven, to the detriment of its channel. Thus the drainage of the Black Sluice district is discharged just below Boston; the drainage of the West and Wildmore Fens is discharged into the river, a little lower down, through Maud Foster Sluice; and the discharge of the drainage of the East Fen takes place through Hobhole Sluice, some distance further down (Plate 13, Fig. 6). Accordingly, out of four outlets for the drainage of the Witham basin, only one discharges along the channel of the haven

through the Grand Sluice. Also the outlets of the sluices are at right angles to the river channel, so that much of the scouring effect of the issuing waters is lost.

River Nene. The first suggestion for improving the outfalls of these rivers was made by Kinderley in 1721, who proposed that a straight cut should be made below Wisbeach, towards the sea, for improving the outfall of the Nene. This cut was only commenced in 1770, about five miles below Wisbeach, and was carried out for a length of 1½ miles. Though this cut was considerably shorter than Kinderley had proposed, its effects were sufficient to show that the principle was correct, and that important benefits might result from an extension of the system further down the river. Straight cuts increase the fall of these rivers, which is very defective; they consequently afford a freer discharge to the drainage waters which accordingly have a greater scouring force, and they facilitate the tidal flow up and down which assists in the maintenance of the outfall.

The beneficial effects of Kinderley's Cut were gradually lost, owing to no extension of the work having been carried out. Mr. Rennie, in a report made in 1814, pointed out, that, whilst the fall of the Nene between Wisbeach and Ganthorpe Sluice, a distance of 5½ miles, was only 6 inches, the fall below, from Ganthorpe Sluice to Crabhole, was as much as 13 feet, though the distance was about the same. He concluded that the high shifting sandbanks along the last-named portion of the channel obstructed the discharge above, and recommended the construction of a new cut from the end of Kinderley's Cut to Crabhole. This cut was authorised in 1827; it was carried out under the direction of Mr. Telford and Sir John Rennie, and was opened in 1830. The cut, which is five miles long, was only partially excavated before the river was admitted, whose flow, as anticipated, soon scoured out the channel to the desired size. The scour, in fact, of the fresh and tidal waters combined,

was so effectual, that the sides of the channel had to be protected by stonework. The tidal flow along the river was much improved by the cut so that its effects extended as far up as Wisbeach, five miles above the cut, to such a degree, that buildings had to be protected from being undermined, and low-water mark was lowered more than 10 feet.

River Ouse. The river Ouse, above Lynn harbour, was much improved by substituting a straight cut for the very tortuous channel of the river. This cut, known as the Eau Brink Cut (Plate 13. Fig. 5), was completed in 1821; it lowered the low-water level, at its upper end, about 6½ feet; it admitted a sufficient flow of tide to scour the river up to Denver Sluice, and enabled the sill of that sluice to be lowered 6 feet, which greatly benefited the drainage of the district.

The river has since been improved, below King's Lynn, by a straight cut two miles long, and by training the river, for an additional distance of 1½ miles through the sandy shoals, with banks of fascine work, which has effected a further reduction of 3 feet in the low-water level.

River Witham. The outfall channel of the Witham between Boston and Hobhole, a distance of three miles, was straightened and confined about fifty years ago by banks of fascines, stones, and earth, so as to have a uniformly increasing section seawards. This work improved the channel so much, that the flood tide reached Boston 1½ hours earlier; and vessels of larger draught could get up to the haven.

The lower part of the Witham, between Hobhole and its junction with the Welland, has been, by degrees, similarly trained, under the direction of Mr. Wheeler, engineer to the Boston Harbour Commissioners. Unfortunately the Witham meets the Welland at right angles, so that the flow of the two rivers is considerably impeded at their junction, and they flow on for some distance below in a shallow winding channel (Plate 13, Figs. 5 and 6). A new cut, however, about three

miles long, is being excavated, as shown in dotted lines on the plan, under the direction of Mr. J. E. Williams, engineer to the Witham Outfall Board. This cut commences just below Hobhole Sluice, and rejoins the existing channel at Clayhole. By cutting across the projecting point of the Scalp, it will avoid the sharp bend at the point, and do away with the conflicting junction of the two rivers.

The scheme prepared by Mr. Williams originally included the improvement of the course of the Witham, just above Maud Foster Sluice, by substituting a straight cut for the sharp bend of the river from the town round by the Black Sluice. This portion of the scheme, however, has been abandoned, owing to the opposition of the Black Sluice Drainage Trustees, who probably foresaw that the proposed alteration of the course of the river would lead to their having to maintain the portion of the present channel between their sluice and Maud Foster Sluice, which would tend to silt up. It is, nevertheless, a subject for regret that this proposal is not to be carried out, as it would have greatly improved the channel of the Witham at a very defective part, and, by aiding in the improvement of the outfall, would probably have more than compensated the Black Sluice Trustees for the loss which they undoubtedly would have experienced in having to keep open the abandoned channel.

There is every reason for anticipating that the new cut in progress below Hobhole, and the projected widening and deepening of the river through Boston and above the Grand Sluice, together with the enlargement of the Grand Sluice, will considerably improve the condition of the outfall, and largely benefit the drainage above.

River Welland. The outfall of the Welland was much improved by training the river with fascine work for $3\frac{1}{2}$ miles below Fossdyke Bridge, which lowered the low-water level 7 feet at the bridge; but want of funds has prevented the continuation of this work down to the junction with the

Witham. The new cut on the Witham will lead to the diversion of the Welland into its old southern channel, so that the rivers will in future have independent outfalls. It would appear, however, from the state of the estuary (Plate 13, Figs. 5 and 6), that this arrangement will give the Welland a circuitous outlet, and that it would be advisable, if possible, to train the channel of the Welland so that it might join the Witham at the lower end of the new cut. By this means, whilst the present awkward junction of the two rivers would be altered, their volume would be combined with advantage in maintaining a common outlet.

Improvement of the Outfalls. The Fen rivers fall into an estuary which is gradually silting up, and accordingly the maintenance of their outlets will always require careful attention. Unfortunately the outfalls had been so long neglected that the harbours on them have lost their importance; and the works, tardily undertaken, have been stopped short of their proper limits for want of funds. The best channel, that of the Ouse below King's Lynn, would require three miles additional length of training banks to convey it to deep water; and the silting up on each side that would follow the extension of the training banks would necessitate their prolongation sooner or later. The improvement of the outfalls, by the completion of the training works to deep water, would not only afford a better depth of water to the ports, but also, by lowering the low-water level and increasing the tidal scour, would greatly facilitate the discharge of the drainage waters. The landed proprietors would find it better to devote funds to the improvement of the outfalls, rather than to additional drainage works in their respective districts; and if they could be induced to co-operate with the Commissioners of the harbours, as is being at length done on the Witham, the interests of all would be greatly advanced by a comprehensive scheme of training works in the estuary.

General remarks. The improvement effected at the mouth

of the river Liffey shows how converging piers, arranged so as to receive a large quantity of tidal water within the area they enclose, and discharging it, at low water, through a contracted opening, can increase the depth at the entrance. These works really almost amount to the formation of an artificial harbour; but the river forms the nucleus of the improvement works, with its natural channel and fresh-water discharge, and it also provides a sheltered channel inland very suitable for quays.

The works at the mouths of the Wear, the Yare, and the Adour, are more strictly river works, as they merely consist in guiding the outlet of the river into deep water; but the increase in depth thus gained is comparatively small. It is very doubtful whether an extension of the jetties, at the mouths of the Wear and of the Yare, into deeper water, would secure any permanent advantage. Probably the foreshore would gradually advance, till the outlet returned to its original state, with the disadvantage of an additional length of jetties having to be maintained. The prolongation of the jetties along the entrance channels of the harbours on the southern coast of the North Sea has proved of little avail; and large sluicing reservoirs, and dredging, have had to be resorted to for increasing the depth. Dredging and increasing the tidal reservoir area might be further employed for improving the outlets of the Yare and the Wear; but the methods are costly, and a dredged channel has to be constantly maintained. The only other method of improving the outlet, in such cases, is protecting it by solid piers, extending into deep water, enclosing a large area, and converging at their extremities; but this can only be resorted to where there are no outlying sandbanks, and where the expected increase of trade justifies a large outlay. This plan has been adopted for Aberdeen harbour, at the mouth of the Dee, whose outlet was first improved by parallel jetties; also at the mouths of larger rivers, as will be described in the following Chapters;

and, as already noticed, at the outlets of the Suez and Amsterdam Canals.

It is possible that an extension of the jetties at the mouth of the Adour might be attended with more satisfactory results, as the shore shelves rapidly, and therefore deep water could be more easily reached, and the progression of the foreshore would be more gradual.

Where the outlet channels of rivers meander across sand-banks in a sheltered estuary, as in the case of the Fen rivers, the only plan of improvement is to train the outlets within straight and gradually enlarging channels into deep water. By this means the tidal flow is increased, the fresh-water discharge is facilitated, and consequently the channel is deepened and more easily maintained. Accretion of sand and silt behind the banks is an inevitable consequence; but the land thus prepared for reclamation, would far more than suffice for defraying the cost of future extension, and the rate at which extension would need to be carried out would decrease as greater depths are reached.

CHAPTER XV.

IMPROVEMENT OF TIDAL RIVERS (*continued*).

Instances of Tidal Rivers; Differences in their Conditions. Rivers in a Naturally Good Condition; *The Thames;* its Past and Present state; *The Humber. The Mersey;* Peculiarities in the Form of its Estuary; Objections to its Improvement above Liverpool. *The Scheldt;* Variations in its Condition between Antwerp and the Sea; Quay Works at Antwerp; Barring of the East Scheldt, its Effect on the Western Scheldt; Schemes proposed for the Improvement of the River. *The Dee;* Training Works and Reclamation of Land in its Estuary, Injurious Effect on the River.

MOST of the larger tidal rivers have had some works executed on them; but the extent of these works varies considerably in each case, in proportion to the defective condition of the channel in its natural state, and the requirements of the trade which passes along it. The most interesting instances to engineers are those where large river works have been carried out with successful results; but those rivers whose condition is naturally good deserve a brief consideration, as illustrating what forms of channel and estuary, and what local conditions, specially conduce to the easy maintenance of a river. Also works which have proved either partially or wholly unsatisfactory, are very useful as warnings against attempting similar works under similar circumstances.

The Thames and the Humber furnish instances of rivers whose natural condition is very good, and on which few works have been accomplished, within recent times, materially affecting the state of their channels. The Mersey is an instance of a river whose outlet is somewhat unstable, and the depth of

whose channel is only just adequate for the demands of navigation, but where hitherto no works of improvement have been carried out. The Scheldt, though totally different in form from the Mersey, resembles it in having a somewhat unsatisfactory outlet, for the improvement of which no extensive works have hitherto been adopted; though works have, in this case, been proposed in view of the gradual silting up of the estuary. The history of the Dee shows what injury may result to a river from the training of its channel, more with the object of land reclamation than the improvement of the river.

The works in the estuary of the Seine, and at the mouth of the Maas, afford capital instances of large works of improvement judiciously designed and efficiently executed, but which, though in many respects successful, seem liable to be impaired by unforeseen results.

The Tyne, the Tees, and the Clyde, are examples of the extent to which tidal rivers of moderate size may be improved, where expense is of little consequence provided a deep channel can be attained.

River Thames.

This river has been already mentioned as one of the few rivers that, as regards navigation, may be said to be free from a bar. The depth of its channel from London to the sea seems to be due to the form of its estuary, gradually widening out as it approaches the sea, for it possesses no very special advantages either as regards the rise of tide, which is about 16 feet 2 inches at spring tides at Sheerness, or the discharge of fresh water from the river at Teddington, amounting on the average to 3,250,000 tons a day. Indeed the advantage of the form of its estuary is manifested by the fact that the range of spring tides is greater at London Bridge than at its mouth, being 20 feet 9 inches at London, which is 4 feet 7 inches more than at Sheerness. However, at the close of

the last century the range of spring tides at London Bridge was only 15 feet, so that it has increased 5 feet 9 inches during the present century. The river is embanked between London and the sea; but the period when these works were executed, or the state of the estuary previous to their formation is not known.

Though the river widens out as it descends to the sea, its channel is by no means perfect; it has numerous expansions and contractions in width, and consequent variations in depth; there are several bends in its course, and the sandbanks at its mouth shift, and produce accordingly alterations in the outlet channels. There appears, however, to be no tendency for shingle or sand to accumulate at its entrance, owing to the great width and depth of the estuary, and the deeply recessed bay into which it opens placing it well out of the influence of any drift along the eastern coast of England. In fact the condition of the estuary is so good from natural causes, that the ancient embankment works, though carried out for land reclamation, and consequently without any attempt to regulate the course of the river, have doubtless improved its channel without injuriously diminishing the depth at its mouth. The reduction of depth, which actually occurs at its mouth, and which would constitute a bar if the depth, amounting to about 20 feet at low water, was considerably less, is a matter of no consequence under existing conditions.

The improvement in the tidal condition of the river near London Bridge and above, is due to the removal of Old London Bridge at the beginning of the century, and to the subsequent removal of the old bridges at Westminster and Blackfriars, which were replaced by bridges having fewer piers and more ample waterways. The removal of gravel from the bed of the river for ballast and other purposes, and the dredging of shoals in the channel, have also materially contributed to the improvement in the range of tide. Old London Bridge acted as a sort of weir across the river, with

its numerous piers resting upon wide foundations which were eventually still further extended by a protection of pile work, for the bed of the stream had sunk to a lower level than the foundations of the piers. The foundations of the bridge had evidently been originally laid upon the river bed which was subsequently lowered by scour, induced probably, partly by the rush of water through the arches of the bridge, and partly by the regulation of the channel below by embankments. The removal of these various obstructions has enabled the tide to flow up more freely and for a longer period, and has consequently increased the scouring power of the ebb tide, which has deepened the channel, and has also prevented the accumulation of silt which used to take place owing to the checking of the tide at Old London Bridge.

The Thames embankments within the metropolitan area were undertaken for the benefit of London, and not as a measure of river improvement. Though a portion of the foreshore of the river has been reclaimed by these works, and the tidal capacity of the channel has, accordingly, been somewhat reduced, which has not been quite compensated for by an increased depth, nevertheless the minimum width of the river, in these parts, has not been encroached upon, and the flow has been facilitated by the regulation of the channel. Accordingly these embankments, whilst improving the depth through London, have produced very little alteration in the tidal flow; and any injury they may have caused below by diminishing the tidal capacity could be easily compensated for by improvements elsewhere in the channel.

The excellent condition of the Thames, owing to the free admission of the tide and the form and naturally good position of its estuary, is clearly manifested by the small effect which the discharging of all the sewage of London, and the dirt from the streets, into the river produces on the channel.

Additional dredging of shoals, and the rebuilding of Waterloo Bridge, whose waterway is reduced by the rubble

mounds protecting the piers, would render the state of the river perfectly satisfactory.

River Humber.

This river, which is in reality the estuary of the Ouse and the Trent, resembles the Thames in widening out gradually as it approaches the sea, and in being free from a bar affecting navigation, though it is always densely charged with silt, which it rapidly deposits in any sheltered creek. The width and depth of its navigation channel have rendered it unnecessary to execute any works for its improvement. There exist, however, considerable variations in the depth of the channel, which is liable to slight alterations in its course. The mouth of the estuary is somewhat contracted by the projection of Spurn Point, which is gradually forcing the channel towards the south. The estuary was formerly very wide within Spurn Point; but, owing to the contraction at the outlet, extensive reclamations were effected in the estuary, which regulated the tidal flow up the river without unduly reducing the depth at the outlet.

River Mersey.

The form and condition of the tidal portion of the river Mersey are totally different from those of the Thames and the Humber (Plate 14, Fig. 1). The river is narrow and winding from Warrington to a little distance below Runcorn, where it enters a broad sandy expanse which is covered at high water, and through which the low-water flow winds in a shallow and shifting channel. The estuary contracts again considerably on approaching Liverpool, and the river flows between Liverpool and Birkenhead, for a distance of about six miles, in a very deep narrow channel which opens into the Irish Sea, and it finds an outlet through two or three channels between shifting sandbanks.

The main or Crosby Channel has a bar, with a depth of

about 10 feet over it at low-water spring tides; but this, though comparing unfavourably with the low-water depths in the Thames and the Humber, does not materially impede the navigation, as the mean range of tide is about 21 feet, rising to 26 feet at ordinary, and 31 feet at equinoctial spring tides. The outlet channels have undergone several alterations; but as soon as one main outlet begins to silt up another has formed, so that in spite of these changes there appears to be no perceptible progress of deterioration in the estuary.

The tidal area of the river has been slightly encroached upon, in front of Liverpool, by the Liverpool Docks; but, as these works have served to regulate the channel, no perceptible interference with the tidal flow has been caused by them; and the broad tidal area above has been left almost unaltered.

The condition of the river above Liverpool has formed the subject of considerable discussion. It would be impossible to improve its depth without confining its channel by training banks, which would lead eventually to the reclamation of a large portion of the existing tide-covered area between Runcorn and Liverpool. The gain to the river above Liverpool from such works would be considerable; but the reduction of the tidal receptacle would reduce the scouring power of the current in the estuary below, and would in all probability lead to a deterioration of the outlets. The river has, accordingly, been left in its natural condition; as a good channel between Liverpool and the sea is of far greater importance than the extension of the navigation higher up the river.

An improvement and fixation of the outlet channel might be effected by diverging embankments below Liverpool; but the depth over the bar is sufficient for present requirements, owing to the large tidal range. Embankments would be very costly, and their effect on the deposits in the estuary uncertain. Accordingly, unless unforeseen changes occur in the condition of the outlet channels necessitating remedial

measures, it is probable that the Mersey will remain an instance of a river really very defective as regards the variations in the depth and width of its channel and the restricted limits of its navigation, but which it would be inexpedient to improve, as it is naturally just adequate for the requirements of the most important port on its banks.

River Scheldt.

The tidal portion of the river Scheldt is of considerable importance, as it forms the navigable channel to Antwerp, the principal port of Belgium, and also gives access to Flushing, and to Terneuzen, the port of approach to Ghent by the Ghent-Terneuzen Canal (Plate 15, Fig. 4). The Scheldt enters the North Sea through a wide estuary, and its tidal portion extends as far up as Ghent, a distance of 110 miles, and the tide would flow even higher up if not stopped at Ghent by the gates of La Pécherie lock.

The river between Antwerp and Doel is fairly regular in width, enlarging somewhat as it descends. It has indeed some sharp bends, the embankments on each side have been constructed without any attempt at uniformity of line, and some forts project rather injuriously into the river; but considering that these matters have, as usual, been left to chance, the river is in a tolerably good condition along this part of its course. This section of the river might be much improved by modifying the embankments, removing the projecting points, and easing off the curves, assisted if necessary by a little dredging. The tidal flow would be facilitated by these works, and the tidal range at Antwerp increased, which even now is 15 feet 2 inches at spring tides, only 4 inches less than at Doel, and 2 feet 6½ inches greater than at Flushing.

The condition of the river changes abruptly below Doel, as the river enters there a larger estuary, through which its low-water channel follows a winding course, between large sandbanks, to the sea. The navigation channel, after passing

near Bath on the right bank, turns towards the centre of the estuary, and approaches the left bank near Welsoorden. Then it pursues a devious course round the projecting land of Ossenisse, and, after approaching the right bank again near Point Mires, it passes across to the opposite bank, and continues close along it in the curved reach in which Terneuzen is situated. A little below Terneuzen it crosses over to the right bank, passing between the Suiker Plaat and Hooge Springer banks in the middle of the estuary, and it keeps close to the right bank as far as Flushing. The mouth of the river below Flushing is encumbered by numerous sand-banks, between which navigable access to the sea is obtained through two or three principal channels, of which the Wielingen channel, passing close along the Belgian coast, is the best.

The estuary itself, which is very wide opposite Bath, contracts considerably opposite Waarde, after which it again expands, narrowing again opposite Flushing, and then opens out into the North Sea.

The navigable channel through the estuary, besides being circuitous, is irregular in width and depth (Plate 15, Figs. 4 and 5). The shallowest place is at the frontier, a little below Doel, where the depth is 18 feet 4 inches at low water; and below Bath the least depth is 21 feet, and, except in a few places, exceeds 26 feet at low water. As the smallest rise, at spring tides, which occurs at Flushing, amounts to 12 feet 7 inches, the depth of water in the channel is satisfactory, as is evident from the fact that, in spite of the long and winding channel up to Antwerp, the trade of that port is increasing rapidly.

Under these circumstances it is natural that no works of any importance have been undertaken for the improvement of the river. Two large works, however, affecting the condition of the river must be briefly alluded to, namely, the quay works at Antwerp, now in progress, and the barring of the East Scheldt, which was carried out in 1867.

Improvement Works at Antwerp. The quays at Antwerp are being constructed to accommodate the growing trade of that port, with which the increase of dock accommodation cannot keep pace. They will, however, also rectify the right bank of the river in front of the town; and by extending into the river where it is broad, and cutting off a projecting point where it is narrow, they will regulate the width of the river at that part, and assist in maintaining its depth, which is being increased by dredging. For a shoal existed in front of the town with a depth of only 15 feet 5 inches of water over it at low water.

Barring of the East Scheldt. The barring of the East Scheldt, near Bath, was executed simply for the purpose of carrying a railway to Flushing; an embankment being preferred to an open viaduct, which it would have been both difficult and costly to construct on such a silty foundation (Plate 15, Fig. 4). The proposal, however, gave rise to a keen controversy with reference to its probable effect on the Western Scheldt. Some of the engineers, called in to advise on the matter, considered that the embankment, by leading to the silting up of the portion of the estuary between it and Bath, would diminish the tidal receptacle, and consequently produce a deterioration in the depths of the channel between Bath and the sea; whilst other engineers were of opinion that, owing to the peculiar tidal flow through the East Scheldt, its barring would not materially diminish the tidal volume entering the Western Scheldt. All the engineers were agreed that the work would benefit the river above Bath, by directing the tidal waters straight into the upper river instead of allowing them to extend laterally into the East Scheldt. These last anticipations have been fulfilled, as the tidal range above Bath has been slightly increased since the embankment was made.

The East Scheldt was formerly the principal branch of the Scheldt; but by degrees, owing to the tendency of the rivers

on that coast to seek a more southern outlet where the range of tide is greater, the Scheldt deserted its eastern branch, and the Western Scheldt became the principal outlet. The tide entering the Western Scheldt used to fill a large part of the East Scheldt, between Bath and Berg-op-Zoom, before the tide from the eastern mouth arrived; and consequently the East Scheldt contributed to the tidal capacity of the West Scheldt. Of the volume of tidal water, however, poured into the East Scheldt from the West Scheldt during flood tide, only one-third returned into the West Scheldt during the ebb, so that two-thirds of the whole, amounting to about 27,500,000 cubic yards, were lost to the ebbing waters of the western branch, and transferred to the eastern branch. This preponderance of the flood tide over the ebb in the Western Scheldt must have been prejudicial to the maintenance of its outlet; and the first results of the embankment must have been beneficial. For, though the volume of the flood tide introduced may have been somewhat diminished, the volume of the ebb tide has been augmented. The silting up of the portion of the eastern branch between Bath and the embankment will eventually reduce the tidal capacity of the Western Scheldt; but this must have resulted sooner or later from the conflict of the flood tides meeting in the eastern branch between Bath and Berg-op-Zoom. On the whole the West Scheldt estuary appears to have gained rather than to have lost by the barring of the eastern branch, owing to the loss of ebb waters that occurred, and the irregularity which the lateral dispersion of the tide at Bath produced on the flow up the river. Even now the tidal range, which increases from Flushing to Bath, becomes reduced about 7 inches at Doel; but this will doubtless be modified when the enclosed portion of the East Scheldt is finally silted up, and if the shoals are dredged between Doel and Bath.

Proposed Improvement of the West Scheldt. Though the navigable channel of the Scheldt, between Antwerp and

the sea, has hitherto fulfilled all the requirements of navigation, the condition of its estuary is such as to arouse some anxiety about its future; for whilst the draught of vessels is continually increasing, the depth of the channel in some places is barely sufficient, and recourse to dredging has been proposed. The restoration also to the river of the drainage waters of its basin, abstracted for drainage improvements and the supply of canals, has been advocated; and any further grants of reclamation embankments encroaching on the river have been forbidden.

The gradual silting up of the estuary appears, however, to be inevitable, judging from the obliteration of the adjacent creeks to Damme and Sas de Gand previously alluded to; and sooner or later some comprehensive remedial measure will have to be adopted for preserving the depth of the channel through the estuary. Two schemes have, indeed, been already proposed, which are shown in dotted lines on Plate 15, Fig. 4; they are interesting as indicating the difference of opinion which exists on the important subject of the regulation and improvement of tidal rivers by embankments.

According to Herr Caland's plan propounded in a book on the effect of tides on rivers[1], published by him in 1861, the estuary would be merely regulated by embankments so as gradually to enlarge as it approaches the sea, the deep indentations being shut off by curving banks. M. Behr, however, taking the works executed on the Clyde and the Seine as his models, proposes to train the river in as straight a course as possible, within banks slightly widening out as they descend, but enclosing such a contracted channel that the river would be restricted to one-fifth of its present estuary[2].

The first plan resembles the arrangements adopted for the old embankments of the Thames below London, which have

[1] Étude sur l'Effet des marées dans la partie maritime des fleuves. P. Caland, p. 80.

[2] Travaux Hydrauliques. Chambre des Représentants de Belgique, No. 174, Mai, 1878.

proved so satisfactory; and whilst regulating the form of the estuary, and consequently improving the tidal flow up it, would not so diminish the tidal capacity of the estuary as to compromise the maintenance of the outlet.

The second plan does not appear to have been framed with a due regard to the necessity of the tidal ebb and flow for maintaining the depth of an outlet channel across the numerous sandbanks at the mouth of the Scheldt; and though probably the method proposed would secure a better depth in the regulated channel itself, by increasing the efficiency of the fresh-water discharge, this would be of no avail if a channel beyond of equal depth could not be obtained. Considering that the requisite depth at the outlet is only just attained with the existing large tidal ebb and flow through the somewhat contracted estuary opposite Flushing, it is impossible that a greater depth would be secured when the tidal capacity of the estuary is greatly reduced, unless the training works, instead of stopping at Flushing, were continued across the sandbanks. This would be a very costly undertaking on such an exposed coast, and one which even such a great advocate of the embanking of tidal rivers as M. Bouniceau has acknowledged that he shrinks from proposing.

The important differences which exist between the conditions of the estuary of the Scheldt and those of the Seine or of the Clyde will be alluded to in Chapter XVII, after the Seine and the Clyde have been described; but they are such as to render it unadvisable to treat the Scheldt in accordance with the methods adopted for the improvement of those rivers.

River Dee.

Land reclamation frequently results from the training of rivers through shallow estuaries, as a natural consequence of the restriction of the channel. Where, however, the improve-

ment of the river is the main object, the best line is selected for the trained channel, without any regard to the advantage of subsequent reclamations. In the case of the Dee, unfortunately, a reverse principle was followed.

The estuary through which the Dee flows into the Irish Sea is filled with very fine sand, which appears to have gradually accumulated. The natural channel of the river through the estuary was consequently unstable; and undoubtedly, in the early part of last century, it had become clear that the river would have to be trained by banks through the estuary if a proper navigation channel to the port of Chester was to be maintained. A company, however, was formed for the purpose of reclaiming a portion of the estuary. The promoters at the same time promised to provide an improved depth of water up to Chester. In 1737 they made a straight cut for the river, diverting its channel southwards from near Chester towards Flint, away from the original and direct course of the river along the Cheshire or northern shore of the estuary (Plate 14, Fig. 3). This line was adopted on account of its being the most suitable for enabling a large area of land to be reclaimed, which was the real object of the undertaking.

Besides, however, diverting the river from its direct course to the sea, the new channel was so injudiciously directed that it forced the current against a projecting point of land, which made it diverge, on approaching Flint, almost at right angles across the estuary, through which it flows in a winding, shifting channel to the sea. The trained cut, however, by fixing and straightening the channel, did improve the depth of the river at Chester; but the navigable channel has not been maintained there at the depth promised by the reclamation company. This has led to numerous complaints, and to various suggestions for improving the state of the river.

The old works have, however, so prejudicially affected the maintenance of the outlet channel, that its improvement has

become a matter of increasing difficulty. It would be necessary to train the low-water channel of the river in a suitable line from the cut towards the sea, which would fix its course and promote scour; and additional depth would have to be obtained by dredging. The port of Chester, in the meantime, has lost so much of its trade that funds are not forthcoming for any comprehensive scheme of improvement; and the state of the Dee remains as a warning of the injuries that may be inflicted on navigation from attention being mainly directed to land reclamation. Had the river been originally trained by low banks along the Cheshire coast, with some regard to the natural bends of the channel, it is probable that with the good rise of tide, amounting to 29 feet 6 inches, at the mouth at spring tides, the state of the river would have been much improved, and Chester might have remained a flourishing port.

CHAPTER XVI.

IMPROVEMENT OF TIDAL RIVERS (*continued*).

The Seine: its Former Condition; Difficulties of Navigation to Rouen; Embankment of its Channel; Effect on the Channel; Advantage to Rouen; Rapid Silting up of the Estuary outside the Channel; Injury to Havre. *The Maas:* Changes in its Estuary; Alterations in the Navigable Channel; the Voorne Canal; New Works; Adoption of Scheur Branch and Cut across Hoek-van-Holland; Jetties at the Mouth; Result on Trade to Rotterdam; Expected Depth at Mouth not attained; Causes of this Result. Comparison between the two rivers; Influence of Tidal Flow.

THE present Chapter will be devoted to the consideration of two tidal rivers, the Seine and the Maas, whose natural condition was so defective that extensive works have been carried out for their improvement.

RIVER SEINE.

Previous to the year 1850, the navigable condition of the Seine between La Mailleraye and the sea was very unsatisfactory. The state of the river between Rouen and La Mailleraye, a distance of 37 miles, was fairly good, as, though the depths were variable, the channel was fixed. Below La Mailleraye, however, the width of the river became very variable, so that whilst it was 820 feet wide at La Mailleraye, it reached a width of 1570 feet to the right of the Vernier marsh. The river, moreover, was encumbered with shifting sandbanks which, under the influence of the currents, were continually altering the position of the navigable channel; so that frequently, in the course of a few days, the channel shifted from one bank to the other. The depth also was

irregular and variable. Above Quillebeuf the depth was insignificant, and below it there was an available depth of only 14 feet at the highest tides, and 5 feet 9 inches at high water of neap tides. The navigation, moreover, was exposed to numerous dangers which were aggravated by the *bore*, a wave generated by the flood tide, which rushes up estuaries with a great velocity under certain conditions[1]. Vessels of only between 100 and 200 tons navigated the river with difficulty. The journey from the sea to Rouen, a distance of 74 miles, occupied four days; only vessels drawing not more than 10½ feet could get up to Rouen, and these only at certain states of the tide.

Embankment of the Tidal Seine. M. Bouniccau published, in 1845, a valuable work on the navigation of tidal rivers[2], in which he proposed that the Seine, below La Mailleraye, should be improved by means of longitudinal embankments. The scheme, suggested by M. Bouniceau, was approved by the Chamber of Deputies, who sanctioned the improvement of the river by rubble training banks as far down as Quillebeuf; and these works, which were commenced in 1848, were completed in 1850 (Plate 16, Fig. 1). An increased depth having been obtained by this means, the work was continued; and between 1853 and 1857 a single bank was formed, on the southern side of the channel, from Quillebeuf to the point of La Roque; but as this bank did not succeed in directing the deviated channel, a second bank was constructed, in 1861–2, on the northern side of the channel, parallel to the other, and by 1869 the double embankment had been extended to Berville. The work has been stopped at this point, as a proposed further extension of the northern bank for 1¼ miles was objected to in the interests of Havre. The channel has been

[1] When the entrance channel of an estuary is obstructed or circuitous, and the rise of tide is considerable at its mouth, the flood tide has to rise some height before it can overcome the obstacles to its progress, and at last flows up the estuary with a rapid current, or wave, known as a *bore*.

[2] Étude sur la navigation des rivières à marées. M. Bouniceau.

given a width of 984 feet at Villequier, enlarging to 1312 feet at Quillebeuf, and to 1640 feet at Tancarville, which amounts, on the average, to a widening out of 1 foot for every 200 feet in length. The banks consist of rubble mounds of chalk protected by pitching, as shown in the sections (Plate 16, Figs. 3 and 4).

The embankments have been carried out in accordance with the lines laid down by M. Bouniceau as far as they go; but his scheme embraced the prolongation of the double line of banks as far as Honfleur, with an extension, on the southern side, to the northern edge of the Trouville bank, and a possible future continuation of the northern bank in a westerly direction, or of both banks towards Havre. The banks have been raised above high-tide level, on the right bank to a little below Tancarville, and on the left bank to La Roque; but below these points, banks submerged at high water have been adopted, in order that, whilst regulating the low-water channel, they may conduce less to the deposit of silt in the estuary behind them.

Results of the Tidal Seine Embankments. The effect of the works on the portion of the river between the embankments has proved most satisfactory (Plate 16, Fig. 2). The level of low water at Rouen has been lowered 2 feet $3\frac{1}{2}$ inches at spring tides, and 2 feet $9\frac{1}{2}$ inches at neap tides; whilst the level of high water has been only lowered about half an inch. In some places the bed of the river has been deepened as much as 29 feet. The Meules bank, a little below La Mailleraye, is the shallowest place on the river, but it has been lowered 10 feet by dredging, and there is now never less than 15 feet 9 inches over it at high-water neap tides. The least depth lower down is 21 feet 8 inches. The journey to Rouen occupies one or at most only two tides; and the navigation up to Rouen has been rendered so much more secure, that the price of insurance has been reduced from $\frac{1}{2}$ per cent. per ton to the same price as at

Havre, and the cost of carriage from 10 francs per ton to half that amount.

The portion of the estuary below the embankments is subject to alteration, which renders the navigation somewhat difficult in that part. However, vessels of 2000 tons have managed to get up to Rouen, and in 1877 the 'Tyro,' drawing 21 feet, accomplished the passage. The length of river regulated by the embankments is about 25 miles, and the distance from the termination of the embankments to the actual sea is about 10⅝ miles.

Though the works from La Mailleraye to Berville have proved a complete success as regards the navigation of the river to Rouen, raising that town to the position of the fourth port in France, and, moreover, have enabled 21,250 acres of land to be reclaimed, there is another aspect of the case which is by no means satisfactory.

M. Bouniceau, besides foreseeing that his scheme would produce a great improvement in the depth and fixity of the channel, was also fully aware that the embankments would gradually lead to the silting up of the estuary behind them. He considered, however, that this action would be very slow, owing to the small amount of silt apparently available as gathered from observations of the wasting action along the adjacent coast. He thought that the alluvium, washed up and deposited behind the banks, would be brought in the first instance from the Trouville bank together with the detritus from the neighbouring shores; and he estimated that a period of 21,000 years would elapse before the deposit, after having raised the large tracts in the bay behind the embankments, reformed the sandbanks, in front of Trouville and the estuary, to their original heights before the works were commenced. It is evident, from his book, that he considered the silting up behind the embankments, and subsequent deterioration at the mouth of the estuary, so remote, that it was needless to take it into account.

Experience has shown that he enormously underestimated the quantity of deposit that was available for silting up the bay, and which made its appearance so soon as the flow of tide in the bay had been modified by the embankments. The flood tide continues to bring up sand into the estuary; but the ebb, whilst having a much greater effect within the embanked channel, thus increasing its depth has been withdrawn, in a great measure, from its former wide-spread scouring action over the whole bay, which was sometimes more efficient in one part and sometimes in another, and which, though injurious to the navigable channel, deferred the inevitable silting up of the estuary. The fresh-water discharge of the Seine, which is very considerable in flood time, has indeed been concentrated in the embanked channel, giving a greatly increased efficiency to the ebb in the channel, but enabling the flood tide to preponderate elsewhere.

Accordingly, stagnation occurs outside the main channel, and deposit is rapidly taking place, whilst the supply of alluvium brought in by the flood tide appears to be inexhaustible. Moreover, in proportion as the upper portions of the estuary are raised, the tidal area becomes smaller, the scouring action outside the navigable channel is diminished, and accretion goes on with increasing rapidity.

No records appear to exist of the rate at which accretion was going on in the estuary of the Seine before the embankments were commenced. It has been possible, however, by the help of some statistics, given by M. Estignard in a report on a survey of the estuary of the Seine[1], to form some idea of the changes taking place there. It appears from an investigation of M. Estignard's figures that the amount of silt which accumulated in the western portion of the bay, between 1869 and 1875, was double that which had accumu-

[1] Reconnaissance hydrographique de 1875 à l'Embouchure de la Seine. Rapport par X. Estignard, 1877.

lated during the previous six years. The rate of deposit for 1875 may be reckoned at more than 13,000,000 cubic yards over the western portion of the bay; and it appears that the yearly rate of deposit doubled in a period of six years. The total actual loss of tidal water entering the estuary, through silting up, since the works were commenced, after making allowance for the increased volume in the deepened channel, is estimated by M. Estignard at 274,000,000 cubic yards. Now M. Bouniceau, in his book, estimates the amount of alluvial deposit necessary to raise the portions of the estuary of the Seine outside his proposed embankments to the level suitable for reclamation, at 823,000,000 cubic yards, or only a little over three times the quantity of deposit which, according to M. Estignard's calculations, has already accumulated in the estuary. At the date of M. Estignard's report barely thirty years had elapsed since the commencement of the works, and already one-third of the deposit had taken place which M. Bouniceau thought would occupy an almost indefinite period in accumulating; and, moreover, the rate of deposit has increased with marvellous rapidity. Not only behind the banks, but also beyond the termination of the banks, large tracts of land have emerged from the sea.

Rouen has gained so much by the works that changes in the estuary are of little importance to it, so long as a good outlet channel can be maintained to the sea. Also the reclaimed lands are an important gain, both to the State and the riparian proprietors. Moreover, as the tidal currents maintain a good depth of water outside the bay, and as the Seine brings down a large volume of fresh water, it is probable that by an extension of the training banks to the sea-coast, a good navigable channel may be maintained, even when the silting up of the bay has destroyed the reservoir of tidal water which has maintained it in the past. The embankments, however, have produced such rapid changes in the estuary that additional works will be required far

sooner than could have been anticipated; and it is impossible, at present, to predict what works of protection and maintenance will eventually be required on the sea-coast for securing a permanent deep-water outlet channel.

The future of the port of Havre, at the mouth of the Seine, has been seriously compromised by the embankment works. Up to the present time the flood tide, having gained a predominant influence over the ebb, appears to have washed some of the sand from the banks in front of the estuary, and deposited it higher up, thus to a slight extent realising the anticipations of M. Bouniceau. This action has slightly improved the approaches to Havre; but M. de Rochemont, the engineer of the port, naturally considers that this is merely a very temporary gain, and that the silting up, which has taken place in the estuary to the east of the port, will gradually extend to the west, and injure the entrance to the harbour, which is even now hardly deep enough for the vessels frequenting the port. It is evident from the results of M. Estignard's survey that before long Havre must be brought under the influence of the rapid accretions in the bay; and unless the new channel of the Seine is trained so as to flow close to Havre, that port will be ruined by the improvement of the river.

River Maas.

The Maas, and the branches of the Rhine known under the names of the Leck and the Waal, find an outlet into the North Sea through a number of channels situated between the mainland of South Holland and the Western Scheldt. Continual changes have been taking place in these channels, partly owing to natural causes, and partly to reclamations of land commenced in the ninth century. The earlier reclamations tended to concentrate the numberless channels into a certain number of definite outlets, but later reclamations have occasioned a silting up of some of these outlets. The general

tendency is for the north-eastern channels to silt up, and the south-western channels to become the main channels, partly in consequence of the increased tidal range towards the south, and partly owing to the reclamations. Thus the vessels trading with Rotterdam, which used to navigate either the Scheur branch, which is the northern and most direct outlet of the Maas, or the Brielle branch, which William III entered, in 1691, with his whole fleet (Plate 15, Fig. 1), were forced to seek more southern and circuitous channels. For these outlets deteriorated so rapidly, that by the middle of the eighteenth century the bar at the mouth of the Brielle channel was hardly passable by fishing boats. This deterioration has been aided by reclamations of foreshore, reducing the tidal area of the New Maas from 10,840 acres in the earlier half of the eighteenth century to 7,260 acres in 1850.

At the beginning of the present century, vessels drawing more than 10 feet could not enter by the Brielle channel, but had to go round by Hellevoetsluis and Dordrecht; whilst vessels of more than 16½ feet draught could not pass by the Haringvliet channel to the Hollandsch Diep, but had to enter by Brouwershaven and go up the Grevelingues, Krammer, and Volkrak channels to the Hollandsch Diep, and thence by Dordrecht to Rotterdam. The inconvenience of this latter very circuitous, and in some parts intricate, channel was so great that the Voorne canal was constructed, in 1829, through the island of Voorne, from Hellevoetsluis to the Brielle branch of the Maas, thus avoiding the Brielle bar, and, whilst using the deeper entrance at Hellevoetsluis, escaping the shallow and circuitous channel by the Haringvliet. The Voorne canal was, however, only made sufficiently large to meet the requirement of the then existing trade, and proved inadequate for the larger vessels with greater draught subsequently introduced.

New Outlet for River Maas across Hoek-van-Holland. A better channel of access to Rotterdam being thus urgently

needed, various schemes were submitted, in 1857, to a Commission of Dutch engineers, for providing a channel having a minimum depth of 23 feet. The Commission having reported, unanimously, in favour of a scheme presented by Herr Caland, it was decided, in 1862, to carry it into execution. The design consisted in reverting to the Scheur branch of the Maas, the most direct approach to Rotterdam, and providing it with a new outlet by cutting through the projecting neck of land known as Hoek-van-Holland (Plate 15, Fig. 1). In order to convey the new outlet into a depth, at high water, of 23 feet, which was attained closer inshore at the site selected than elsewhere along the neighbouring coast, nearly parallel jetties were built out from the shore, 2790 feet apart, and their outer portions were only raised to half-tide level, so that, whilst concentrating the ebb, they might not impede the flow of the flood tide up the river. The abandoned portion of the old channel of the Scheur was dammed off, so that the whole of the current might be diverted into the new cut (Plate 15, Fig. 2). The scheme also included the training of the river as far up as Krimpen, above Rotterdam, so as to regulate its width. The width of the channel was made to increase regularly as it descended, commencing at a width of 738 feet at Krimpen, increasing to 1476 feet at Vlaardingen, and reaching 2953 feet at the extremities of the jetties.

The cut across Hoek-van-Holland was only partially executed by manual labour. As soon as a narrow shallow channel, between one-third and one-fourth of the full dimensions, had been made across the point of land, a length of three miles, the water was admitted; and the widening and deepening of the channel was accomplished by the tidal scour and river current aided by dredging.

Jetties at Mouth of River Maas. The jetties were constructed of fascine work, secured by piles, and weighted with stones (Plate 2, Fig. 2). It was originally intended that the northern jetty, 2187 yards long, should project

beyond the southern jetty, so that the flood tide which comes up from the south might have freer admission to the river, and that the entrance might be protected from north-westerly winds, which are the most stormy winds in those parts. However, as it was found that the ebb current, flowing across the mouth of the river towards the south, raised the bar, the southern jetty was lengthened from 1312 yards, at which it had been stopped in 1868, up to 2515 yards, which length was reached in 1877.

Results of Works at Mouth of River Maas. The full depth of 23 feet at high water, which was promised and anticipated from these works, has not been realised hitherto; the largest draught of any vessel which has reached Rotterdam being about $19\frac{3}{3}$ feet. In fact, according to the most recent chart (Plate 15. Fig. 2), the depth at ordinary low water is only 15 feet in the worst part of the main channel between the jetties, which is over the bar at the outlet; and the rise at spring tides is only 6 feet 7 inches. Also the 5 mètre (16 feet 5 inches) line, which originally approached to within 1100 yards of the coast at the site of the works, extends now about 820 yards beyond the ends of the jetties in front of the centre of the channel, though the south jetty just overlaps it. The end of the north jetty was constructed in $26\frac{1}{3}$ feet depth of water: but the depth there is now slightly less than $16\frac{1}{2}$ feet, and the 5 mètre line extends a long distance in front of it. It is evident that the foreshore has progressed considerably, more especially on the northern side, and that neither the run of tide across the ends of the jetties, nor the outgoing ebb, have been able to maintain the original depth of water at the entrance.

The movement of the foreshore in the next few years will be a matter of considerable importance, as upon the question, whether the shore has reached a position of equilibrium, or whether it is still advancing, will depend the maintenance of the works hitherto executed. In the present state of the entrance

it ought to be possible to acquire and maintain the requisite depth by dredging; but if the foreshore continues to advance it may be necessary to extend the jetties.

For the present, at any rate, a far better entrance, both in directness and, for the most part, in depth, has been obtained for Rotterdam than it formerly possessed; as is rendered sufficiently evident by the Voorne Canal route having been almost deserted, and by the great increase in trade since the new route was opened. Thus the tonnage of the vessels coming to and leaving Rotterdam, which was 2,333,000 tons in 1869, reached 3,463,000 tons in 1875, and of this latter amount only 481,000 tons, or less than one-seventh of the whole, were conveyed along the Voorne Canal, which was the main route before the completion of the new works.

Causes of Deficiency in Depth at Mouth of the Maas. The possible causes to which the incompleteness of the success achieved by these works may be attributed are well deserving of a careful consideration. The scheme adopted was unquestionably the best of those proposed; but, as already noticed, the tendency of the Maas, as well as of the Scheldt, is to seek an outlet in its southern branches, whereas the new works have forced it back into its most northern branch, which it was gradually abandoning. To this extent the works were undertaken in opposition to the natural laws in operation on the coast, and of course without training jetties leading into deep water would not have been attempted. It was, however, reasonably hoped that the river, being led into deep water, would be able to maintain its outlet. No doubt some progression of the foreshore was anticipated, but this progression was increased by the commencement of the jetties before the new cut was opened, which acted like groynes on the sandy coast; and to the sand thus accumulated between them was added a considerable portion of the sand washed from the cut. This heap of sand has been gradually pushed outwards since the opening

of the channel, and doubtless accounts for the very remarkable progression of the 5 mètre line right in front of the entrance. It remains to be seen whether the outgoing current will be able gradually to push this accumulation into deeper water, as it is clear that the littoral current across the ends of the jetties has no power of removing it at its present depth.

The new cut was intended to be made as wide as the width between the jetties; but the natural scour has excavated a deeper channel, which, however, is little more than one-third its proposed width (Plate 15, Figs. 2 and 3). This contraction must produce an irregularity in the flow, and lead to stagnation, and consequent deposit, above and below the cut. It must also diminish the tidal ebb and flow, upon which the maintenance of the outlet channel mainly depends, as the admission of the full volume of flood tide must be hindered. In addition, a portion of the flood tide which flows up the river and enters the side branch leading to the Voorne Canal does not all return on the ebb, and is consequently lost to the main channel.

It would be quite possible to remedy most of these defects; by placing gates across the branch channel to the Voorne Canal; by enlarging the width of the new cut; and by removing the accumulations of sand between the jetties by dredging. A further progression of the foreshore could only be provided against by an extension of the jetties, or by forming groynes along the coast to arrest the sand before it reaches the jetties.

Comparison between the Seine and the Maas. The methods of improvement adopted on the Seine and the Maas are very similar; both rivers have been trained in channels gradually widening out as they descend. The enlargement in the case of the Seine amounts on the average to 5 feet for every 1000 feet in length; whilst on the Maas it is about 10 feet for every 1000 feet between Krimpen and

Vlaardingen, and about double that amount between Vlaardingen and the sea. The extent of the enlargement of the Seine channel has been objected to by M. Malézieux as being the cause of shoals appearing in the channel when the discharge of fresh water is very small; and M. Behr attributes the deficiencies of the works on the Maas to the widening out of the channel at too great a rate, more especially below Vlaardingen. When, however, it is considered that estuaries and rivers which are in very good condition frequently enlarge at a much greater rate, amounting occasionally to 50 feet additional width for every 1000 feet in length, the increase of width adopted for the Seine and the Maas cannot be reckoned as large. If the maintenance of their channels depended solely upon the discharge of the river, a restriction of the channel would increase the scour of the current and improve the depth. In a tidal river, however, a great reduction of the channel occasions a great reduction of the tidal volume passing and repassing the entrance, and this is of more vital consequence than the gain of a better depth in the channel above. The value of even such a small rise of tide as occurs at the mouth of the Maas is evident, from the depth that has been maintained at its various outlets, compared with the depths which exist at the mouths of rivers flowing into tideless seas and possessing a much larger fresh-water discharge, such as the Nile.

The Seine is much more favourably situated by nature than the Maas, as the rise of tide at its mouth, and its fresh-water discharge, are considerably larger, and the coast at its outlet is less flat. But the outlet of the Seine is already beginning to suffer from the reduction of the tidal area of its estuary. Probably the Seine would have been in a more satisfactory state, at the present time, if half-tide training banks had been adopted; as the diminution of its tidal capacity would have been thereby deferred, to the advantage of its outlet, without the deepening of its channel being prevented.

As the fresh-water discharge of the Maas is comparatively small, the maintenance of its outlet is in a great measure dependent, especially in the summer, on the tidal ebb and flow, which ought to be promoted rather than reduced; and consequently, it would appear that Herr Caland has not erred on the side of providing too large a channel. The want of adequate depth at the outlet is due to the natural defects of the site, to which was added the encumbrance of the material washed from the cut. As, however, a deep-water outlet has been provided for Amsterdam, by the harbour works at Ymuiden, on the same coast, there is reason to hope that, by supplementary works and dredging, a sufficient depth will be attained at the mouth of the Maas.

CHAPTER XVII.

IMPROVEMENT OF TIDAL RIVERS (*continued*).

The Clyde: Original Condition of the River: Successive Improvements; Cross Jetties; Removal of Shoals; Longitudinal Training Walls; Dredging; Changes Effected; Necessity of Maintenance. *The Tyne:* Description; Projecting Jetties; Training Walls; State of River; Piers at Mouth; Deepening by Dredging; Results of Works. *The Tees:* Short Cuts; Timber Jetties; Training Walls; Dredging; Removal of Hard Shoal; Reclamations; Breakwaters; Results of Works. Comparison between the Clyde, the Tyne, and the Tees. Concluding Remarks on Tidal River Improvement; Training Banks, considerations respecting their Height, Width apart, and Direction; Limits of Improvement Works at Mouth; Converging Breakwaters and Parallel Jetties.

THE tidal portions of the larger rivers of Great Britain, leading to the principal ports, have not needed extensive works of improvement; but the increasing prosperity of some ports situated on smaller rivers, has led to improvements in these rivers of proportionately greater magnitude than those effected on the Maas and the Seine. Whilst the results of training the currents of these smaller rivers have necessarily been less than those attained on the Seine, artificial means of deepening by dredging have been largely resorted to, so that the rivers have been completely transformed.

The Clyde and the Tyne are the most notable instances of such improvements, and the Tees is making progress in the same direction.

The methods adopted for improving these rivers, though similar in many respects, present some points of contrast; and their history furnishes a remarkable illustration of the lengths to which tidal river improvement may be carried, when a rapid increase of trade, and the prosperity of a port, justify taxing to the utmost the resources of engineering skill.

River Clyde.

The Clyde, which in its natural state was a small stream encumbered by shoals, possesses one most important natural advantage. It flows into a deep, wide, and long estuary, which, under the name of the Firth of Clyde, extends from Greenock to the sea. Its outlet is therefore most effectually protected and secured, so that no difficulty is experienced in maintaining it. Considering that the improvement of the depth of the outlet of a river, across a shallow beach and exposed to waves and littoral currents, is generally the most difficult problem in river improvement, it must be acknowledged that the Clyde is peculiarly favoured in this respect (Plate 17).

Improvement of River Clyde by Jetties and removal of Hard Shoals. In the middle of the last century, the Clyde was such an insignificant river that it was fordable on foot at Dumbuck Ford, more than twelve miles below Glasgow; and there were numerous shoals higher up[1]. In the year 1773 Mr. Golborne commenced the system of contracting the river by jetties, so that it might scour itself out a deeper channel; and he also removed hard gravel shoals, by dredging or ploughing, which the current was unable to act upon. In the two following years the channel across Dumbuck Ford was made 7 feet deep and 300 feet wide, at low water, by dredging; and six years later it was found that the natural scour of the river had lowered it to 14 feet.

At the beginning of the present century, Mr. Rennie erected more than two hundred additional jetties, and constructed low rubble training walls connecting the ends of the jetties, to render the channel uniform in width, and to prevent the slipping in of the accumulated deposit on the banks, and the consequent formation of shoals. Also, as the original jetties had been constructed to no uniform lines, he regulated

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxxvi, p. 124.

them by reducing several in length, and lengthening others, so that the river might become a uniformly enlarging channel as it approached the sea. The widths which he fixed for the river were, 180 feet just below the harbour of Glasgow, enlarging gradually to 696 feet at Dumbarton Castle. The increase, however, in the size and number of the vessels frequenting the port became subsequently so great, that the river has been widened to 370 feet at the lower end of Glasgow harbour, enlarging by degrees to 1000 feet at Dumbarton Castle. The low training walls were gradually raised, in proportion as the ground behind them became higher either by natural silting up or by the deposit of material dredged from the river, and the land was reclaimed. Quays were gradually extended along the banks of the river; and, from 1807, the river was continuously deepened, widened, and straightened, for a period of about thirty years.

Improvement of River Clyde by Training and Dredging. In the year 1840 a large and carefully considered scheme of improvement, designed by Mr. James Walker, was authorised; and it is in accordance with the lines then laid down that the subsequent widening and improvement of the river have been conducted (Plate 17).

The principles of improvement on the Clyde have consisted, from the commencement, in removing hard natural shoals; in contracting and straightening the river, first by projecting jetties, and subsequently by longitudinal training walls, which induced deepening by scour; and, lastly, in dredging to obtain a greater depth than the scour of the current in the trained river could effect.

The extent to which dredging has been carried out on the Clyde is very remarkable, as between the years 1844 and 1871, nearly corresponding to the interval between two of the longitudinal sections given in Plate 17, about 14,000,000 cubic yards of material had been dredged from the river. From information kindly furnished by Mr. James Deas,

engineer to the Clyde Trustees, it appears that the total amount of material dredged, up to the 30th of June 1880, had reached 23,606,400 cubic yards; and the greatest quantity of dredging accomplished in a single year, namely in 1878–9, amounted to 1,502,700 cubic yards. The dredged material was for some years deposited on the lands adjoining the river, but since 1862 it has been taken down the river and deposited, by means of steam hopper barges, in very deep water in Loch Long.

Results of Works on River Clyde. The result of the improvements, which have been carried on continuously during the present century, has been to convert an insignificant stream into a deep navigable river, as shown by the longitudinal sections of the channel (Plate 17), which, by Mr. Deas' aid, have been carried up to a recent date. For whereas, in 1755, the depth at Glasgow was only 1 foot 6 inches at low water; in 1830 vessels drawing 15 feet of water could use the harbour; and the depth was gradually increased, so that in 1870 vessels of 22 feet draught were able to get up to Glasgow. Also whilst, only a few years ago, vessels drawing over 15 feet of water occupied two or three tides in passing up or down the river, vessels drawing 22 feet could reach the sea in a single tide in 1873; and now the available channel is 24 feet deep, at high water, from Glasgow to Port Glasgow.

The range of spring tides is 9 feet 1½ inches at Port Glasgow, and 11 feet 2 inches at Glasgow; whereas, in 1834, with a range of 11 feet at Port Glasgow, it was only about 7 feet at Glasgow. The range at neaps is 9 feet 2 inches at Glasgow. Also whereas, in 1837, the time of high water was 1 hour 23 minutes later at Glasgow than at Port Glasgow, it had been reduced to 1 hour 5 minutes in 1873. Low-water level has been gradually lowered 8 feet at Glasgow since 1758, of which 13 inches are subsequent to 1853, when a sort of bar existed at the outlet, as shown in the longitudinal section. High water at ordinary spring tides has been

raised about 9 inches at Glasgow since 1853, and it is now about two or three inches higher than it was in 1758. The lowering of the low-water line is the natural consequence of the regulating and deepening of the river, which has facilitated the ebbing out of the tide. The fall of the high-water line between 1758 and 1853 must be due to the freer discharge of the fresh waters formerly penned up, and to the larger volume of water required to fill the channel, both owing to the enlargement of the channel itself, and also to the lowering of the low-water line. The recent rise of the high-water line is due to the freer access of the tide up the straightened and regulated channel, more especially since the deepening effected at the outlet subsequent to 1853.

General Remarks on Clyde Improvement Works. The improvement of the river Clyde possesses some important peculiarities. The hard shoals, which were dredged from the channel, were natural obstructions which, once removed, unlike shoals of silt, had no tendency to reform, and they had prevented the river forming as good a channel as it was capable of, owing to the inability of its current to scour the shoals.

As the mouth of the river is situated on a deep and well-sheltered estuary, it is not exposed to the importation of sand stirred up by the waves from the bottom, during a storm, or washed in from the beach. Accordingly, the only deposit that can accumulate in the river channel must come from the silt brought down by the river, from the sewage and other refuse of Glasgow, and from the sandbanks opposite Port Glasgow and Greenock, which afford but a limited supply when compared with that of an open sea-coast. The depth, however, of the channel has been long ago carried to an extent which the current is quite unable to maintain, and it is constantly being increased to meet the requirements of the navigation, so that each year the channel is becoming more artificial in its character, and its maintenance more costly.

Mr. Deas, in his paper on 'The River Clyde,' read at the Institution of Civil Engineers in 1873, stated that out of 992,354 cubic yards of material dredged from the channel in the previous year, 300,000 cubic yards were estimated to be deposit from the upper part of the river and from the sewers[1]. Also it will be observed, from a comparison of the longitudinal sections in different years (Plate 17), that whereas the very great increase in depth between 1758 and 1839 was attained with comparatively little excavation, the smaller, though considerable, deepening of the river between 1839 and 1871 necessitated the removal of about 14,000,000 cubic yards of material, whilst the much smaller increase in depth between 1871 and 1880 was only obtained by nearly 10,000,000 cubic yards of dredging.

The river Clyde is not, in reality, merely an improved tidal river, capable of maintaining itself by the aid of the increased and regulated tidal ebb and flow and the fresh-water discharge; but it should rather be regarded as a greatly improved natural channel from a port to deep water, whose depth has been increased so far beyond its natural limits that it has to be constantly maintained by artificial means.

River Tyne.

The river Tyne has been frequently compared to the Clyde, because both the system of jetties and training walls, for contracting and regulating the channel and concentrating its scour, and also dredging, have been resorted to for its improvement. It differs, however, from the Clyde in some important particulars. It was originally in a better condition than the Clyde, and is a somewhat larger river. Its course was not impeded by hard shoals; but, instead of opening into a deep sheltered estuary, it flows direct into the North Sea (Plate 18, Fig. 1). Newcastle, the port for which the river had to be improved, is 10½ miles from the sea-coast. The river between

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxxvi, p. 196.

Newcastle and the sea was very irregular in width, its navigable channel was winding, and a bar existed at its mouth. Up to 1842 no improvements had been effected, and at that period there was a depth, at the shallowest place, of only 2 feet at low water, and 14 feet 6 inches at high-water spring tides; and the high-water level at Newcastle was sometimes from 7 to 10 inches lower than at the sea.

Improvement of River Tyne by Jetties. The work of contracting and regulating the channel, by projecting jetties at suitable places, was commenced by Mr. Brooks, in 1843, who was Engineer at that time to the Tyne Commissioners[1]. The error committed, in the first instance, on the Clyde, of unduly narrowing the channel by making the jetties project too far into the river, was avoided on the Tyne; and the ends of the jetties were eventually connected by low training walls of rubble and slag, after the spaces between them had been partially filled up by the deposit of silt in the slack water. These works, which were continued till 1858 with only a small assistance from dredging, produced a marked improvement in the river, so that the shallowest place in the river attained a depth of 18 feet of water over it at high-water spring tides. The average high-water level at Newcastle had attained the same level as at the sea, which was a gain of about $8\frac{1}{2}$ inches since 1842; and the low-water level had been lowered from 14 to 18 inches. Up to this period, 1858, the improvement of the river had been almost wholly effected by training the river, so as to cause the scour of the current to remove the shoals. The amount of improvement was small, and had been accomplished slowly, but, being produced by natural scour, the river was sure to maintain its depth, and the cost of the works was moderate. The depth of the river, however, was far from satisfactory, as may be seen by an inspection of the longitudinal section of the river in 1860 (Plate 18, Fig. 2). The depth over the bar was only 6 feet

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxvi, p. 398.

at low-water spring tides, and 21 feet at high-water spring tides: the river also above was still much impeded by shoals, and the navigable channel was circuitous.

Harbour and Dredging for Improvement of River Tyne. Piers were commenced in 1856, projecting from the shore on each side of the mouth of the river, to facilitate the removal of the bar, and to protect vessels entering the river from the north-easterly and south-easterly gales prevalent on that coast. The piers consist of a rubble base, surmounted by a superstructure of concrete and stone founded 21 feet below low water (Plate 18, Fig. 3).

A comprehensive scheme, designed by Mr. Ure, the successor to Mr. Brooks, was authorised in 1861 for improving the river from its mouth up to Hedwin Streams, a distance of 19¼ miles. Also in order to convert the harbour, originally designed merely for the improvement of the port, into a regular harbour of refuge, it was decided, on Mr. James Walker's advice, to carry the piers out into 30 feet depth of water, instead of making them converge nearer the shore and terminate in 13 feet of water.

The new scheme consisted mainly in deepening the river by extensive dredging operations. In the twenty years between 1838 and 1858 only 1,500,000 tons of material were dredged from the river, whilst between 1860 and 1881 more than 60,000,000 tons (equivalent to about 40,000,000 cubic yards) have been removed, as much as 5¼ million tons having been dredged in a single year, namely in 1866. This material is, for the most part, taken out to sea in hopper barges and deposited in deep water. The piers also are being carried out as shown on the plan (Plate 18, Fig. 1), and are approaching completion. They converge together towards their extremities, so that, whilst enclosing a large space for vessels and for tranquillising the entering waves, the entrance may be narrowed so as to reduce the swell entering the harbour, and maintain its depth, whilst affording a

sufficient width for navigation, for the flow of the tide up the river, and for the discharge of the river flood waters together with the ebb. It is proposed, by Mr. Ure, and by Mr. Messent the present engineer, to observe the effect of temporarily ending the piers with a width between them of 1800 feet after the works in the upper part of the river are completed, and then to contract the width of the entrance as experience may dictate.

Results of Works on River Tyne. The greatly improved depth obtained by dredging has produced a considerable rise in the tonnage of the vessels frequenting the port; thus, whereas in 1863 only 422 vessels exceeded 500 tons register, the number had risen to 4453 in 1880, of which many were vessels of over 2000 tons[1].

The improvement works are not confined to the river below Newcastle, but are being extended 9 miles higher up. The old bridge at Newcastle, which, like most such old structures, formed a great obstruction to the tidal current, has been removed, and a new bridge built with larger spans, a swing portion traversing the two central spans, of 104 feet each, so as to admit the passage of masted vessels. The alterations in the widths, and the cut through Lemington Point, are shown on the general plan of the river, which, together with the longitudinal sections of the river bed in 1860, 1875, and 1879 (Plate 18, Figs. 1 and 2), has been reduced from a drawing kindly furnished by Mr. Messent.

There is now nowhere a less depth than 20 feet between Newcastle and Shields, and a similar depth over the bar, which amounts to a lowering of 14 feet since 1860. In that year the time of high water at Newcastle was 1 hour 3 minutes later than at Shields, whilst in 1872 the difference had decreased to 23 minutes. The rise of spring tides is 15 feet both at Newcastle and the mouth of the river; and the low-water level at Newcastle has been lowered about

[1] River Tyne Improvement. Description by P. J. Messent, C.E., June, 1881.

2½ feet since 1860. A channel which was dredged across the bar in the harbour, to a depth of 25 feet below low water, did not fill up to the 20 feet level for six years; and, as slopes tend to form on each side of the deepened channel, it is expected that when the channel is again dredged to a depth of five feet below its present level, it will remain considerably longer before it becomes filled up a second time to the 20 feet level.

The improvements previous to 1860 reduced considerably the tidal capacity, as the slight increase in depth, and the concentration of the current, did not compensate for the large area gradually abstracted from the river by the shoaling in the spaces between the jetties. The improvements, however, since 1860, in the portion of the river up to Newcastle, have produced an increased flow of tidal water, in and out between the piers, of 14,000,000 cubic yards; and when the works in the upper river above Newcastle have been completed, the total additional tidal capacity of the river will amount to nearly 20,000,000 cubic yards, which will very materially assist in the maintenance of a channel across the bar at its mouth.

The form of the harbour does not prevent a bar being formed by the sediment brought down by the river, as the current of the river loses its velocity on opening out into the harbour, and accordingly deposits the material it held in suspension. Also any sand brought in from the sea would be similarly deposited in the comparatively still water in the harbour; but, probably owing to the depth of water into which the entrance channel is being carried, the amount thus introduced is small. The harbour, accordingly, protects the mouth of the river from the heaping up action of the sea along the coast; and the narrowed entrance between the piers is certain to be maintained by scour.

There can be no doubt that the extent to which the river

bed has been deepened by dredging exceeds considerably the limits within which the river is capable of maintaining itself by its tidal ebb and flow and fresh-water discharge, and that the present improved channel will have to be maintained by dredging. The actual amount, however, of deposit that will have to be removed every year to maintain the depth, cannot be determined till the works in the upper part of the river are finally completed.

River Tees.

The river Tees was formerly very irregular and tortuous between Stockton and Middlesbrough. At a short distance below the latter town it enters a wide sandy estuary, through which it flows for a distance of about 7 miles before reaching the North Sea (Plate 19, Fig. 1).

Improvement of River Tees by Cuts and Jetties. The first improvement in the tidal portion of the river was made in 1810, when a cut, 220 yards long, was opened near Stockton, which reduced the length of the river by about $2\frac{1}{2}$ miles, and increased the depth at Stockton from 9 feet to 11 feet[1]. Another cut was made in 1830, having a length of 1100 yards, but it was a less advantageous work than the first cut, as, besides costing about double, it did not shorten the river very considerably, and reduced the tidal capacity. About the same period the system of regulating and contracting the river by means of timber jetties, projecting out at right angles to the shore, was introduced, and was carried on till about 1852. By these means a more direct and deeper channel was formed between Stockton and Cargo Fleet below Middlesbrough, a distance of about 7 miles; the increase in depth varying from about 2 to 5 feet. The jetties, however, produced irregularities in the depth, shoaling the channel in some parts and deepening it in others. The works, moreover, by cutting off a large area of tide-covered strand, which

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxiv, p. 64.

was raised by deposit between the jetties, had a somewhat injurious effect on the channel just below. There were also other shallow places in the channel through the estuary, especially where it divided into two branches on each side of the Middle Sand, and also over the bar at the mouth of the estuary. These defects, and the growing importance of Middlesbrough as the centre of a rapidly developing iron trade, led to measures being adopted for improving the channel through the estuary.

Improvement of River Tees by Training Banks and Dredging. A new system of improvement was decided upon in 1853, consisting of guiding the river by continuous longitudinal training walls on each side of the channel, and increasing the depth by dredging. Originally there were three or four variable channels from Middlesbrough to the sea, which were consequently all shallow[1]. The river was trained to follow the more direct southern channel, and the other channels were closed.

The training walls, or banks, consisting of mounds of broken slag from the ironworks, have been gradually extended on each side of the channel through the estuary, and down to the mouth of the river, as shown on the plan (Plate 19, Fig. 1): they have also gradually replaced the jetties in the upper part of the river between Stockton and Middlesbrough. The training walls above Middlesbrough have been raised to half-tide level, whilst those below are only third-tide walls. These walls have regulated the level of the river bed; and an enlarged channel has been provided, gradually widening out as it approaches the sea.

Dredging operations were commenced in 1854, being at first directed to the removal of old shoals, and subsequently to the general deepening of the river. The longitudinal sections in 1853 and 1879 indicate the improvement effected (Plate 19, Fig. 2). Up to 1865 only one dredger was em-

[1] The River Tees. W. Fallows.

ployed, but since that period two, and for a time three, dredgers have been at work. The greatest amount of material dredged from the channel, in one year, was 1,173,520 tons in 1876; and the total amount dredged, since the commencement, up to the end of 1880 had reached 9,570,250 tons, according to information kindly furnished by Mr. John Fowler, engineer to the Tees Conservancy Commissioners, from whom also other particulars relating to the river, contained in Plate 19, have been obtained. A ridge of lias rock, which extended across the channel at the eighth buoy, has been removed by rock-boring machinery: this rock used to act as a sort of hard bar, stopping the ingress of the flood tide and the egress of the ebb, and its removal has effected a great improvement in the tidal flow.

Results of Tees Improvement Works. The result of these works has been that, since 1878, vessels of from 1000 to 3000 tons have been able to be fully laden at Middlesbrough, and to proceed to sea drawing 21 feet of water. It is, however, desired that the river should be navigable by average-sized ships at all states of the tide, and for this purpose Mr. Fowler proposes that, eventually, the depth of the river, at low water, should be increased to 14 feet up to Middlesbrough, and 12 feet from there up to Stockton; but for the present he advises that a channel 12 feet deep up to Middlesbrough, and 10 feet up to Stockton, should be obtained as soon as possible by dredging.

The tidal area of the estuary amounted to about 9000 acres. The reclamation of a certain portion of this area has been authorised; 826 acres have been already reclaimed on the southern side of the estuary, and about 1300 acres remain to be reclaimed on the northern side. The reduction, however, of tidal capacity by these reclamations is small, as these portions were little below high-tide level; and the profits obtained by the Commissioners, from the sale of their share

of the reclaimed lands, help to defray the cost of the improvement works which restore, in the more advantageous form of depth, the shallow tidal area abstracted.

Breakwaters at Mouth of River Tees. Two breakwaters, projecting from opposite shores at the sea end of the estuary and converging together towards their extremities, will protect the entrance channel and increase the scour across the bar (Plate 19, Fig. 1). The South Gare breakwater, which stretches across the Bran Sand to the bar, is designed to have a total length of 4,270 yards. It was commenced in 1863, and consists of an embankment of large blocks of slag, protected on the sea side by a concrete wall extending from a little below low-water to high-water spring tides (Plate 19, Fig. 3). Between three and four million tons of slag have been deposited in the breakwater, and the work is approaching completion. Large cement concrete blocks are to be placed at the termination of the breakwater, forming a circular end which will serve as a foundation for a lighthouse. The approaches to the proposed North Gare breakwater have been commenced, and it is expected that the actual breakwater will be commenced in 1882, and will occupy nine years in construction; its length will be about 2000 yards. The opening at the entrance between the piers is to be 800 yards wide. The cost of the breakwaters is greatly reduced owing to the Commissioners actually receiving payment from the ironmasters for removing the slag from their works, so that the breakwaters are really great spoil banks of slag.

The improvement works have produced a lowering of the low-water level of spring tides at Stockton, to the extent of between 2 and 3 feet; and very high spring tides rise a little higher at Stockton than formerly, owing to the admission of the tide being facilitated.

Comparison between the Clyde, the Tyne, and the Tees. The same principles of improvement have been adopted on all the three rivers described in this chapter. The first step

consisted in the projection of jetties at right angles to the banks, which straightened, confined, and deepened the channel. This system of cross jetties, however, was found to possess two important defects; it produced irregularities in the depth, as the scour of the current is more powerful opposite the ends of the jetties where the channel is most contracted, and therefore a series of hollows and intermediate shoals were formed; it also reduced the tidal capacity of the river, which was unfavourable to the maintenance of the channel below, and especially at the outlet. In every case these jetties were replaced by longitudinal training walls, and their erection could only be justified on economical grounds, as cross jetties, placed at intervals, are cheaper than continuous training walls, and may be useful in producing a small amount of improvement before the revenues of a port admit of a larger outlay. If possible, however, they should be avoided, as they serve merely as a temporary expedient, and involve in the end a greater total expenditure.

Longitudinal training walls, formed of mounds of whatever materials were most readily procurable, were used, in every instance, for connecting the ends of the cross jetties, and for forming a regular channel towards the mouth, enlarging in width as it descends. Local circumstances have prevented the Tyne being trained in as regular a channel as the Clyde and the Tees; but the channel at the 'Narrows' has been widened out from 400 to 670 feet, it has been enlarged to 400 feet in width above Newcastle, and altogether the Tyne possesses the widest channel of the three.

The land behind the training banks has been reclaimed on the Clyde down to Bowling: on the Tyne, it has been either reclaimed or converted into docks; and on the Tees, it has been reclaimed above Middlesbrough, but not near the training banks in the estuary below, as the reclamation banks are quite distinct works for reclaiming land of little value as tidal reservoir space. In every instance, however,

the tidal capacity, lost by reclamations, has been restored or increased by the deepening of the channel.

The first improvements effected by manual labour in the bed of the rivers under consideration consisted in the removal of the worst shoals; and their channels were afterwards uniformly deepened by systematic dredging. The amount of dredging effected in the Clyde is about three times that hitherto carried out on the Tees; and the dredging accomplished on the Tyne is nearly double that done on the Clyde. Whereas, however, the Tees has a minimum depth of about 10 feet at low water of spring tides up to Middlesbrough; the Clyde has a depth of about 15 feet up to Glasgow; and the Tyne has attained a depth of 20 feet at low water up to Newcastle, and 18 feet for about $2\frac{1}{2}$ miles above. The increase of depth gained is, accordingly, somewhat proportionate to the amount of dredging performed.

The Tyne and the Tees, with a tidal range at their mouths of about 15 feet, have the advantage, in this respect, over the Clyde, where the tidal range is only 11 feet, but this smaller rise of tide is comparatively of little consequence owing to the excellent outlet possessed by the latter river. The improvements have in every case produced a considerable lowering of the low-water line: the somewhat anomalous small rise in the high-water line on the Clyde at Glasgow, and on the Tees at Stockton, is attributable to the removal of the shoals near the outlets which impeded the influx of the flood tide.

The works at the mouths of the Tyne and the Tees are very similar in their general purpose and design; but the Clyde is exempted from the necessity of such works by the peculiarly favourable position of its outlet. Whilst, however, the Tyne has a larger channel than the Tees, and a greater fresh-water discharge (its basin having an area of 1053 square miles as compared with the 744 square miles of the Tees basin), the Tees has the advantage of a very wide estuary,

which will provide an efficient scour at the entrance when the breakwaters are completed. The area of the Clyde basin is intermediate between the other two, as it amounts to 945 square miles. It is interesting also to note, with reference to the fresh-water discharge of the Clyde, that, whereas the inundating of the low-lying parts of Glasgow was of frequent occurrence up to 1840, the improvement of the outlet has put an end to these floods.

The Tees is, at the present time, less artificial in its character than either the Clyde or the Tyne; but when the proposed increase of depth by dredging has been accomplished, it will resemble the other two rivers in requiring continued dredging operations merely to maintain the depth attained.

Concluding Remarks on Tidal River Improvement. In the descriptions of the works given in this and the preceding chapters on tidal river improvement, sufficient evidence has been afforded that the training of a tidal river by longitudinal banks always conduces to the improvement of an irregular and shifting channel. On the Seine and on the Maas, on the Clyde, the Tyne, and the Tees, and on the Fen Rivers, the training banks have proved perfectly successful in regulating the flow and deepening the channel.

The only doubtful questions, indeed, with reference to training banks are, how high they should be raised, and how far apart they should be placed.

It is generally unwise to raise the banks above half-tide level, if it can be avoided, as the tidal flow in the estuary is impeded by high banks, which leads to the accumulation of silt behind them, thus reducing the tidal capacity, and affecting the depth at the outlet. It has been seen that the rapid accretions in the estuary of the Seine, caused by high embankments, are compromising the maintenance of the outlet channel. Low training banks will be required sooner or later through the estuary of the Scheldt below Doel, when the gradual

process of silting up shall have unduly reduced the depth of the navigable channel; but the plan of restricting the river in a narrow channel between embankments, high enough for the reclamation of the land on each side, as proposed by M. Behr (Plate 15, Fig. 4), would be fatal to the depth at the mouth, owing to the enormous reduction of tidal area, amounting to four-fifths of the whole. The Scheldt, unlike the Clyde, opens on to an exposed coast, and, unlike the Tyne and the Tees, its outlet channel cannot be led into deep water at a short distance from the shore. Accordingly, the tidal capacity of the estuary of the Scheldt must be carefully maintained for the sake of its outlet, though the depth of its navigable channel may at the same time be improved by guiding it by low training banks in a more direct channel between Doel and Ossenisse. A wise foresight in the case of the Tees, which, though more favourably situated as to its outlet than the Scheldt, flows through a somewhat similar sandy estuary on a much smaller scale, has led to the adoption of low training banks, so as not unduly to restrict the tidal capacity.

The increase in width of the channel between the Seine banks averages 5 feet additional width in a length of 1000 feet; and this is the rate of enlargement on which M. Behr's scheme for the Scheldt has been based (Plates 15 and 16). It is, however, considerably less than what has been adopted in most other instances. Thus the widening out of the Clyde channel is 10 feet in 1000 feet of length, and a similar proportion may be traced on the Tyne, and has been adopted on the Tees. The river Vire also, in France, and the portion of the Maas between Krimpen and Vlaardingen, have been regulated on the same principle. The widening out is greater, however, of rivers which are in a good condition, such as the Thames and the Humber; and the enlargement of the Scheldt between Antwerp and Lillo averages nearly 20 feet for every 1000 feet of length, and a similar proportion has been adopted

by Herr Caland for the regulated channel of the Maas below Vlaardingen. It appears therefore that the rate of enlargement in the regulated channel of the Seine is unusually small.

The free admission of tidal water up a river depends upon the adequate expansion of the channel towards the sea; and it would be advisable, for the sake of the outlet, to make the enlargement somewhat excessive in preference to restricting it within very narrow limits. It is also well that there should be some excess of capacity in the channel, so that any accumulation of silt in the summer may not interfere with the navigation. Also a channel which is only just large enough to be maintained efficiently in summer by the fresh-water discharge, is not adequate for carrying off freely the winter floods.

The direction given to the training banks must necessarily somewhat depend upon the natural line of the river, and upon the position of any ports on its banks. Thus, if the lower portion of the Scheldt was trained, provision would have to be made for the channel to pass close to Terneuzen and Flushing; and when the Seine embankments are extended, they will have to be diverted from their straight course in order to direct the river towards Havre. In consequence, however, of the absence of any port at the mouth of the Maas, Herr Caland was able to alter completely the line of the main channel of that river, and to adopt the most direct and suitable position for the outlet.

The depth to which a channel can be improved and maintain itself, depends on the natural condition of the estuary, the tidal flow, and the fresh-water discharge. All rivers are capable of more or less improvement by training their channels, removing shoals, and giving the river bed a regular fall throughout; and the extent of possible improvement, within the limits of natural maintenance, depends in a great measure on their size. When, however, it is desired to give a river like the Tyne a depth of channel approaching that of

the Thames, which has a drainage area five times larger and a naturally deep estuary, it is necessary to resort to artificial means for acquiring and maintaining the depth. The Clyde and the Tyne have been improved beyond what may be termed their natural limits of improvement; whilst the works on the Seine and the Maas have been conducted, hitherto, on the principle of trying to train the rivers so as to make their natural powers of maintenance as efficient as possible. It seems probable that artificial means of deepening will be found indispensable at the mouth of the Maas, owing to its unfavourable position; but the Seine should be capable of maintaining itself by the help of gradually extended embankments. When the improvement of a river has passed considerably beyond the natural limits, its channel approximates to the state of a mere creek, as the fresh-water discharge bears a very small proportion to the tidal flow. Also the fall of the river bed is sometimes so largely reduced to secure the required depth, as in the case of the Clyde, which is practically level from Glasgow to its mouth, that the natural scouring force is almost lost; and, accordingly, the cost of maintenance grows in an increasing ratio for every additional increase in depth.

The works at the outlet of a river form the most critical portion of the whole scheme of improvement; but when once the system of training through a shallow estuary has been commenced, it has to be extended eventually to the mouth of the river. The system of improving and protecting the outlet channel by means of converging breakwaters, enclosing a considerable tidal area, has been adopted on the Tyne, the Tees, and the Liffey, resembling the ordinary design of artificial harbours in Great Britain; whilst the system of parallel jetties has been adopted at the mouth of the Maas and of the Adour, similar to the method employed for the entrance channels of Dunkirk harbour and other ports on the southern coast of the North Sea.

The advantage of the system of converging piers over the system of parallel jetties is, that additional tidal capacity is provided close to the entrance, which promotes the scour through it, as at the mouth of the Liffey, and also that deposit tends to take place within the harbour, as at Tynemouth, where it is easily removed, instead of at the actual mouth, as in the case of the Maas and the Adour.

The only way in which the shoaling up of the entrance can be avoided when the foreshore progresses, is by carrying the piers far enough out, so as to come within the scouring influence of cross currents, or into such deep water that the progress of the foreshore becomes very slow. Moreover, where piers project a considerable distance from the shore, a state of equilibrium appears to be reached by the foreshore outside the piers, before its influence extends to the entrance, owing probably to the sweep of the littoral currents round any projecting point.

CHAPTER XVIII.

IMPROVEMENT OF THE MOUTHS OF TIDELESS RIVERS.

Deltas: their Shallow Channels; Rate of Progression. *Methods of Improvement:* Jetty System; Side Canals. *Delta of the Rhone:* Jetty Works; Effect on Bar; Progression of Bar; St. Louis Canal. *Delta of the Danube:* Description; Comparison of Channels; Provisional Works at the Sulina Mouth; Effects produced; Consolidation of Piers; Effects of the Extension of South Pier; Results of Works. *Delta of the Mississippi:* Description; Attempted Improvements; Proposals; Jetties at Outlet of South Pass; Construction; Results. Lake River Outlets. Concluding Remarks—Harrowing, Dredging, Jetties, Comparison of the Works on the Danube and the Mississippi.

THE principles of improvement of rivers flowing into tideless seas differ from those hitherto considered, owing to the absence of any tidal influences capable of affecting the maintenance of their outlet channels. The mouths also of tideless rivers are different in form from those emerging on tidal coasts.

DELTAS.

A tideless river, instead of being subjected to an oscillating tidal movement extending to a greater or less distance inland, flows with an unimpeded current to the sea. On reaching the sea, however, the river is checked in its flow, and deposits gradually the sediment with which it is charged. A bank of deposit, accordingly, tends to form in front of the mouth, which by degrees extends out into the sea like a sort of low promontory, through which the river forces its way in a shallow channel to the sea. As the outflow of the river becomes impeded by the bar forming at its mouth, it gene-

rally forms for itself auxiliary outlets at the side, across the low-lying foreshore; and the resemblance these diverging mouths, and the line of coast, present to the letter Δ has led to the name of delta being given them (Plate 20, Figs. 1 and 5, and Plate 21, Fig. 1). The Nile, the Danube, and the Mississippi, are well-known instances of delta-forming rivers.

The river being subdivided into several channels has its velocity and scouring force reduced, which favours deposit: and the shallow channels are quite inadequate to afford a passage for the class of vessels which the size and depth of the undivided river above could easily accommodate. Thus the Rhone, which has a depth of 42 feet at Tour St. Louis, more than 4 miles above its mouth, has only a depth of $6\frac{1}{2}$ feet over its bar: the Neva, with a depth of 65 feet at St. Petersburg, has a depth of only 13 feet over the bar at its mouth: the Danube, with a depth of 50 feet just above its delta, had a depth, at the Sulina mouth, of only from 7 to 12 feet up to 1858; and the Mississippi, which in some places above its delta has a depth of 120 feet, had till recently a maximum depth of only about 15 feet over the bars at its mouths. As the deltas project into the sea, and the principal bars form beyond the extremities of the mouths, the tendency of the waves and littoral currents is to remove or displace the bar, rather than to assist in its formation as is the case in tidal rivers, unless indeed the wind blows directly on shore.

The rate of progression of these deltas, and consequent elongation of their shallow channels, depends upon the amount of sediment brought down by the river, and to a certain extent on its weight, for whilst the heavier particles are deposited, the lightest particles are carried farther out to sea and dispersed; it also depends on the slope of the sea-coast in front. The Rhone delta has been found to have had an average yearly progression of 140 feet in the last 25 years. The advance of the shallows at the Kilia mouths of the Danube is stated, by Sir Charles Hartley, to have amounted

to one mile between 1830 and 1856. The delta of the Mississippi, which extends 220 miles into the Gulf of Mexico, is supposed to have occupied a period of 4,400 years in its formation. The area of the delta of the Danube is 1000 square miles, and that of the delta of the Mississippi is 12,300 square miles. The amount of solid matter discharged annually by the Mississippi is stated by Mr. Corthell, the resident engineer at the delta works, to amount, approximately, to 777,805,550,000 cubic yards[1]. The influence of the sea slope on the rate of progression of a delta is forcibly illustrated by a comparison between the Danube and the Mississippi. Though the Mississippi is estimated to discharge six times the weight of deposit that is discharged by the Danube, the advance of its delta, which amounts to about 207 feet annually, is only about the same as that of the delta of the Danube. This apparent anomaly is very naturally attributed, by Sir Charles Hartley, to the great difference of the sea slopes in front of the bars of these rivers, the slope in the case of the Mississippi being one in sixty-six, whilst at the Danube it is only one in two hundred and sixty-four.

Methods of Improvement.

There are only two methods by which the impediments to navigation produced by a delta can be overcome. Either one of the channels must be regulated, and carried by means of parallel jetties into deep water beyond the bar; or the difficulty must be evaded by the construction of a side canal, issuing from the river above its delta, and entering the sea at some suitable point on the coast, where a deep-water outlet can be secured and maintained.

Jetty System. The first method consists in intensifying

[1] A History of the Jetties at the Mouth of the Mississippi river. E. L. Corthell. p. 15.

and directing the natural current of the river, so as to cause it to scour the bar. The bar is always situated at some distance beyond the mouth of each of the delta channels. This distance depends upon the velocity of the current, and the amount of opposition offered by the prevalent winds or currents to its onward flow; and the crest of the bar is formed where the checked and expanded river deposits the greater part of its sediment. Thus, at the Mississippi delta, the crest of the bar of the South Pass was $2\frac{1}{4}$ miles beyond its outlet, and that of the South-West Pass 5 miles beyond, owing to the discharge through the latter Pass being four-and-a-half times that of the former. By prolonging the banks of the river out to the bar, by means of parallel jetties, the current acts on the bar and forces it into deeper water some distance beyond the ends of the jetties, and the sediment is also carried further out. The deposit, however, continues as before, only its position is altered. Accordingly, the success of the jetty system, in dealing with these outlets, depends on the distance to which these artificial banks are prolonged, the steepness of the slope of the sea bottom in front, and the existence of cross currents to remove the sediment. If no cross currents exist, the bar merely re-forms further out in proportion to the length of the jetties, and the jetties require to be gradually extended. The rate of this extension depends upon the depth attained in front, and the amount of sediment brought down; and, unless the shore is very flat, this rate decreases after every extension.

Side Canals. By substituting a canal for the natural outlet, as the navigable channel, all sedimentary disturbances are avoided, provided the canal is carried entirely beyond the influence of the alluvium of the river. The ancient port of Ostia, which was established by the Emperor Claudius for the purpose of providing a deep-water entrance to the Tiber through a connecting canal, soon silted up, owing to its being situated within the range of the alluvial deposits of the river.

The system of side canals has two important disadvantages; firstly, a canal opening into a tideless sea has no means of providing for the maintenance of its outlet channel by scour, and therefore, unless a site secure from deterioration can be selected, continuous dredging is needed; secondly, the locks and regulating gates necessary on a canal, present a considerable impediment to the rapid passage of vessels, and thus act as a discouragement to trade.

The Rhone is an instance where the jetty system was first tried, and subsequently a side canal was resorted to. The Danube and the Mississippi are recent instances of the successful application of the jetty system; whilst the Nile is an example of a river where the improvement of the river itself through its delta has never been entertained, and a side canal provides communication with the sea. Lastly, the works at the outlets of some of the rivers flowing into the large inland tideless lakes of North America afford examples of a mixed system of improvement by means of jetties and dredging, and, quite recently, by the construction of protecting breakwaters.

Delta of the Rhone.

The river Rhone divides into two branches about half a mile below Arles, and about 31 miles from the Mediterranean Sea. These two branches enter the sea about 30 miles apart, the western branch being called the little Rhone.

Training Banks at Mouth of River Rhone. The principal river entered the sea by four main outlets up to the year 1852. In that year works were commenced for concentrating the discharge of the river into the principal, or eastern channel, by regulating it, on both sides, by embankments stretching out into the sea below, and closing off communication with the other channels above (Plate 20, Fig. 1). It was hoped that the scour of the increased and concentrated current would both remove the bar, and also carry the alluvium of

the river sufficiently far out into the sea for it to be borne away by the littoral current of the Mediterranean, which flows towards the west.

The works were completed in 1857; high earthwork embankments were formed on the land on each side of the channel, and prolonged into the sea by low rubble embankments, which converged slightly towards their extremities, where an opening of 1312 feet was left between them.

Results of Works at Mouth of River Rhone. The depth over the crest of the bar, which was only from $3\frac{1}{3}$ feet to 5 feet in 1852, had increased to from $9\frac{3}{4}$ feet to 13 feet in 1856; but by 1872 it was reduced to $4\frac{1}{4}$ feet. The works, accordingly, have not had the anticipated effect of materially improving the depth over the bar. The failure of this attempt is due to the absence of the assumed littoral current. A current does exist at the surface, but it ceases at a depth of $6\frac{1}{2}$ feet. The sediment therefore of the Rhone is not removed, except to a small extent, by the surface wind-driven current, and deposit takes place as formerly. The closing, however, of the other three outlets has concentrated both the whole discharge and the whole sediment into a single outlet. The effect of the increased current has been to drive the bar further out into the sea; and the effect of the increased amount of sediment has been to make the annual progression of the bar seawards more rapid.

According to M. Malézieux[1], the crest of the bar, which in 1856 was 984 yards in front of the end of the embankments, had extended out to 1640 yards in 1863, and had reached a distance of 2840 yards in 1873, which gives an annual advance of 82 yards during the first period, and 120 yards during the second period. The present rapid advance of the delta gives cause for anxiety as to the maintenance of the outlet of the Bay of Foz, across which the delta is

[1] Cours de navigation intérieure, M. Malézieux. Part i, p. 180.

extending; but this might be checked by opening out again one or more of the old mouths to the west.

The jetty system, in this instance, might have proved more successful if the embankments had been prolonged to the bar, and if they had been turned so that the opening might point in a more southerly direction, which would have brought the discharge more under the influence of the littoral current, and the bar would have been carried more directly out to sea. The embankments, however, would have required frequent extension, in the absence of any efficient cross current, unless deep water could be reached.

St. Louis Canal. As the embankment works did not procure a deep-water channel, the St. Louis Canal was formed, as mentioned in Chapter XII; it was commenced in 1864, and completed in 1873 (Plate 20, Fig. 1). It leaves the river at the Tour St. Louis, opposite the point at which the upper one of the smaller channels diverges from the river, and enters the Mediterranean in the Bay of Foz, to the east of the delta, and therefore out of the influence of the alluvial deposit. The canal, however, will be rendered useless if the progression of the delta bars the outlet of the Bay of Foz, which it will gradually effect if not diverted.

Delta of the Danube.

Channels of the Delta of the Danube. The river Danube divides into two branches 15 miles below the town of Isaktcha, about 45 miles in a direct line from the Black Sea. This point of divergence forms the head of the delta. The northern, or Kilia branch, which conveys seventeen twenty-sevenths of the discharge of the river, pursues an easterly course, and, though frequently divided into separate channels which reunite, it maintains a good navigable depth, till at last, on approaching the Black Sea, it forms an independent delta, splitting up into twelve small channels, through

which it finds an outlet to the sea at a distance of 61 miles from its commencement[1] (Plate 20, Fig. 5).

The southern, or Toulcha branch, which conveys the remaining ten twenty-sevenths of the discharge, after following a south-easterly direction for 11 miles, separates into two channels.

The most northern of these two channels, called the Sulina, which conveys two twenty-sevenths of the total discharge of the river, follows an easterly direction; it is very winding, and only about 300 feet in width; it was impeded by numerous shoals, and was difficult for navigation till within 22 miles of the sea, from whence a good navigable channel exists to its mouth situated at a distance of 63 miles from the head of the delta.

The southern, or St. George, channel of the Toulcha branch, conveying eight twenty-sevenths of the total discharge, follows a south-easterly course, and is 75 miles long; it has a good navigable channel, never less than 16 feet deep, and averaging 1,200 feet in width, though in the centre portion of its course it is very winding. At length it separates, at Olinka Island, into two branches. The Kedrilles branch, going due east, and receiving two-thirds of the discharge of the St. George channel, soon enters the sea, with a depth of from $5\frac{1}{2}$ to $8\frac{1}{2}$ feet over the bar at its mouth. The Olinka branch, going to the south, discharges its waters over a broad shallow expanse.

The Danube, accordingly, which at Isaktcha has a single magnificent channel, 1700 feet broad and 50 feet deep, passes across its delta in three main channels, each of which possessed some impediments to navigation. The Kilia branch, having the largest discharge, naturally possesses the largest channel, and it is also the shortest route to the sea. Its outlets, however, are only navigable for fishing vessels: and,

[1] Minutes of Proceedings of the Institutio of Civil Engineers, vol. xxi, p. 277.

moreover, its delta advances at the average rate of about 200 feet a year. The Sulina branch, besides being comparatively narrow, presented numerous obstacles to safe navigation in its upper portion, though its outlet was deeper than those of the other two channels. The St. George branch offered a good though circuitous channel; but the bar of the Kedrilles mouth extended further out than the Sulina bar, though not as far as the bars at the Kilia outlets.

The improvement of the navigation of the Danube, between Isaktcha and the Black Sea, was entrusted, in 1856, to a European Commission, who appointed Sir Charles Hartley as engineer-in-chief. There was, not unnaturally, a considerable difference of opinion between the authorities consulted, as to which branch should be selected for improvement, each branch having one or more advocates. Sir Charles Hartley, however, rejected the Kilia branch, in spite of its good channel, in consequence of the distance of its bars from the shore, the shallowness of the sea in front, and the rapid extension of its delta[1]. This extension, and the distance of the bars from the shore, are the natural consequences of the greater discharge and therefore stronger current and larger amount of sediment possessed by the Kilia branch. The St. George branch was preferred by Sir Charles Hartley, for, whilst possessing a much better channel than the Sulina branch, its outlet is 18 nautical miles nearer the Bosphorus, it is easier to reach, and, though its bar is further out, the greater depth in front, and the stronger littoral current, would have enabled a channel, once formed, to be more easily maintained. The Sulina branch, however, at that time possessed the only navigable outlet; it was therefore decided, from motives of expediency, to adopt an alternative design of Sir Charles Hartley's, and improve the Sulina outlet, by guiding its channel across the bar by piers of a temporary character,

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxi, p. 283.

postponing permanent works at either the St. George or Sulina mouths for further consideration.

Provisional Piers at the Sulina Mouth. The provisional works at the Sulina mouth were commenced in 1858, and were so designed that they could be converted into permanent works, if it should be eventually considered desirable to adopt the Sulina mouth as the permanent outlet. The design consisted of two piers projecting, on each side of the mouth, across the bar, and terminating in a depth of 18 feet of water. The object aimed at was to concentrate the river current between the piers, and so deepen the channel across the bar; and it was hoped that the current would have sufficient impetus to carry the sediment within the influence of the littoral current which flows towards the Bosphorus. The temporary piers were constructed of a rubble mound and piling surmounted by a timber platform, 14 feet wide, strengthened at intervals by strongly built timber cribs of the same width. The northern pier, 5332 feet in length, follows an easterly direction, turning slightly towards the north near its extremity. The southern pier, 3457 feet long, commences at a point of land some distance to the south, and converging towards the north pier, finally runs parallel to it across the bar, with a width between them of 600 feet, which is the normal width of the river near its mouth (Plate 20, Fig. 2). The north pier was, in the first instance, made to overlap the south pier for a length of 600 feet, in order to shelter vessels entering or leaving the harbour from the prevalent northerly and north-easterly winds.

The works were sufficiently nearly approaching completion by the close of 1860 to produce a marked improvement on the bar. The bar was lowered 2 feet in the first three months; and the first high flood, in 1861, being confined within the piers, instead of raising the bar as formerly with the sediment brought down, scoured away the bar, and

formed a channel with a minimum depth of 16½ feet and 500 feet wide, where previously the depth varied between 7 and 12 feet.

Consolidation of the Piers at the Sulina Mouth. As the effect of the provisional works proved so satisfactory, and as there was no chance of raising adequate funds for improving the St. George branch, it was decided, in 1866, to consolidate the piers at the Sulina mouth, and convert them into permanent structures. This was accomplished by forming a superstructure, or concrete wall, on the top of the rubble mound, by depositing the concrete in cases 'in situ' along the shore ends of the piers. Along the outer portion, a wall of concrete blocks, each weighing 18 tons and cemented together by concrete filling, was built upon the levelled rubble base; and the outer slope was protected by concrete blocks, of from 10 to 20 tons in weight, deposited at random on the rubble mound[1] (Plate 20, Figs. 3 and 4). These works, commenced in 1868, were completed in 1871.

It was found that, in the absence of high floods, sand accumulated against the projecting portion of the north pier during the prevalence of south-westerly winds, which reduced the channel at that place to a depth of 15 feet, with a width of only from 100 to 150 feet. To remedy this unsatisfactory condition, the south pier was extended 457 feet in 1869, parallel to the north pier, in order to prolong the scouring action of the current, and scour away the accumulations of sand against the end of the north pier. The value of this extension became manifest on the commencement of the floods at the beginning of 1870. For whilst early in January of that year the depth at the mouth was only 16½ feet, it was increased to 18½ feet in February, and by the end of March it had attained 22 feet. Full particulars of these works are

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xxxvi, p. 201.

contained in two papers, by Sir Charles Hartley, read at the Institution of Civil Engineers in 1862 and 1873 respectively.

Effect of the Piers at the Sulina Mouth. In 1872 an effective depth of channel of 20 feet for navigation was obtained, and has been maintained, thus affording an increased depth of 11 feet since 1857.

The works, besides improving the channel, have retarded the advance of the delta opposite the Sulina mouth; for whereas the advance of the 24 feet and 30 feet lines of soundings averaged 94 feet in a year previous to the commencement of the works, it only amounted to 44 feet in a year from 1861 to 1871. This retardation must be attributed to the transportation of the sediment by the littoral current across the piers, since the river discharge has been forced into deeper water by its concentration between the piers. The anticipations, therefore, formed at the outset, have been fully realised, both as regards the effect of the piers on the channel and the action of the littoral current. The reduction in the rate of advance of the delta is very satisfactory in relation to the maintenance of the outlet channel, as it will defer the period when the jetties may have to be extended.

The progression of the Kilia delta towards the south is, accordingly, more liable to prove injurious to the maintenance of the Sulina outlet than the small advance of the Sulina delta, whose discharge, and consequently proportion of sediment, is only one-ninth of that of the Kilia branch.

Delta of the Mississippi.

The delta of the Mississippi is generally assumed to commence a little below the confluence of the Red River, where a small stream issues from the Mississippi and discharges into the Gulf of Mexico.

Passes of the Delta of the Mississippi. The Mississippi has a deep and comparatively narrow channel from the head of its delta to near its mouths. At Fort St. Philip,

and for some distance above, it has a channel averaging 2470 feet in width and 120 feet in depth. About twenty miles below Fort St. Philip, and fifteen miles from the Gulf of Mexico, the river widens out to about $1\frac{3}{4}$ miles, and its depth is reduced to 30 feet. At this point it divides into four main channels, or passes as they are called, which, diverging in a fan-shaped form, convey the waters of the river into the Gulf (Plate 21, Fig. 1).

The following table, taken from a paper by Sir Charles Hartley on the Mississippi[1], furnishes the dimensions and proportions of discharge of the four main Passes.

Name of Pass.	Length to outer crest of Bar.	Mean Width.	Mean Depth.	Mean Area of Cross Section.	Proportional Discharge.
	Miles.	Feet.	Feet.	Square Feet.	
South-West Pass	17	1,200	58	70,000	0·34
South Pass ...	14	700	34	24,000	0·08
North-East Pass	16	2,500	37	92,000	0·225
Pass à l'Outre ...	15	1,300	36	47,000	0·254
Remainder mainly through South-West Pass					0·101

At extreme high water the Mississippi discharges 1,210,000 cubic feet of water, and 2000 cubic feet of solid matter, into the Gulf per second.

At extreme low water it discharges about 250,000 cubic feet of water per second, and very little sediment in proportion. The bars, accordingly, which obstructed all the outlets of the passes, were pushed out into the Gulf during the flood season; the bar in front of the South-West Pass progressing at the rate of 300 feet in a year, at the rate of 260 feet at the Pass à l'Outre, and 100 feet in a year at the South Pass.

The average rise of tide in the Gulf of Mexico is only 14 inches, and along the face of the delta there is only one tide in a day. Accordingly, the Mississippi occupies the position

[1] Minutes of Proceedings of the Institution of Civil Engineers, vol. xl, p. 200.

of a tideless river equally with those rivers flowing into the Mediterranean and into other inland seas or lakes.

Improvement of Passes by Dredging and Jetties. The earliest attempts to deepen the channels appear to have been made in 1726, by dragging harrows over the bars. A proposal was made in 1835 to deepen the North-East and South-West Passes by dredging; but the small sum granted by Congress was mainly expended in purchasing dredging machinery[1]. The North-East Pass having deteriorated, the South-West Pass was used at this period as the navigable channel. In 1852 a Board, appointed to report on the subject, recommended that the following methods should be tried in succession till one was found to succeed, namely; stirring up the deposit on the bar; dredging; parallel jetties along the South-West Pass, and closing the other outlets; and, lastly, if all other methods failed, the construction of a side canal. The methods of dredging or parallel jetties were approved of; and the deepening of the channel by dredging was carried out across the bar of the South-West Pass, making it 18 feet deep and 300 feet wide. This channel, however, was filled up with deposit by 1856; and a sum was voted by Congress for opening and maintaining a channel, 300 feet wide and 20 feet deep, through the South-West Pass and the Pass à l'Outre, either by closing the other passes, or by training these two by means of parallel jetties. The jetty system was adopted, and a pile dam, 5733 feet long, was constructed along the east side of the South-West Pass across the bar. The contractors, however, having then exhausted their funds, were unable to make a jetty on the opposite side of the channel, and carry the two jetties further out, which alone could have led to satisfactory results. Accordingly, as the jetty system proved too costly, the contractors, in order to comply with the terms of their contract, resorted to the alternative, but temporary, expedient of dredging, and made a channel, 300 feet

[1] Transactions of American Society of Civil Engineers, 1875, p. 104.

wide and 18 feet deep, through the South-West Pass, and the Pass à l'Outre, in 1858. As the contractors, however, were unable to continue the work of maintenance, the channel filled up again.

A channel, 18 feet deep, was again opened out through the South-West Pass, by dredging, in 1859–60; and the work of maintenance, though interrupted by the American Civil War, was subsequently resumed by the Government.

Alternative Proposals of a Ship-Canal, or Jetties at Passes. In 1873, a Board of Engineers was appointed, with General Barnard as president, to report on the alternative project of a ship-canal into Breton Bay from the river about 5 miles below Fort St. Philip, first proposed in 1832, by which the bar could be avoided. The majority reported in favour of the canal, owing to the uncertainty of the success and cost of maintenance of the jetty system. General Barnard, on the contrary, advocated that the possibility of improving one of the Passes should be fully investigated; as an open channel, unimpeded by locks, was, in his opinion, the only way in which adequate accommodation could be provided for the rapidly increasing traffic. The canal project not being approved by Congress, the question was referred to another Board in 1874, who reported in favour of the jetty system being applied to the improvement of the South Pass.

Improvement of South Pass Outlet by Jetties. In 1874, Mr. Eads offered to make and maintain a channel, 28 feet deep, through the outlet of the South-West Pass for a given sum of money[1]. He objected to the adoption of the South Pass on account of the existence of a shoal, at the head of the Pass, which would be difficult to remove, and also because the narrowness of the Pass would be inconvenient for the navigation of the growing trade. Congress, however, insisted that the South Pass should be the channel selected for the

[1] A History of the Jetties at the Mouth of the Mississippi river. E. L. Corthell. p. 25.

improvement, on account both of its being the Pass chosen by the last Commission of Inquiry, and also of the considerably smaller cost of the works. Accordingly Mr. Eads agreed to construct the necessary works, for obtaining a channel 30 feet deep through the outlet of the South Pass, for the sum of £1,052,000, and to guarantee its maintenance for twenty years for an annual payment of £75,000. This undertaking was authorised by Congress in March 1875.

The South Pass, previous to the commencement of the works, had a width of from 600 to 800 feet, and a minimum depth of 25 feet throughout its course of 13 miles, except for a length of about half-a-mile at the head of the Pass, where it leaves the main river, in which part there was a shoal with a depth of only 15 feet of water over it. The depth also over the bar at its mouth was only 8 feet. It was therefore necessary to deepen the channel at both extremities of the Pass.

The plan proposed by Mr. Eads for improving the outlet of the South Pass was the same as was recommended by the Commission, namely, the concentration of the river current across the bar by means of parallel jetties; and the work was commenced in June 1875. The jetties amount to an artificial prolongation of the banks of the South Pass across the bar for a distance of two-and-three-quarter miles. They are constructed of a pile of mattresses formed of willow, each 100 feet long, 2 feet thick, and varying in width from 40 feet at the foundations to 20 feet at the top (Plate 21, Fig. 3). The jetties are placed along each side of the channel, 1000 feet apart, which was the distance considered necessary to secure them against being undermined by the intensified current, and they are gradually curved a little towards their extremities, so that the outlet may be, as nearly as practicable, at right angles to the littoral current flowing from the east (Plate 21, Fig. 2).

The jetties are raised to flood-tide level, with the exception

of the last 1000 feet. The inner portions of the jetties are consolidated at the top with a layer of rubble stone; the outer portions are consolidated by large blocks of concrete, for a length of one mile along the east jetty, and about half-a-mile along the western jetty. The blocks are increased in size towards the sea ends of the jetties, varying from $3\frac{1}{2}$ feet wide, 3 feet thick, and 16 feet long, to 13 feet wide, 5 feet thick, and 55 feet long, the heaviest blocks, placed at the end of the east jetty, weighing more than 260 tons (Plate 21, Figs. 4 and 5).

In order to promote the scouring effect in the centre of the channel, wing-dams, or spurs, of willow mattresses, 100 to 300 feet in length, were carried out into the channel, at right angles to the jetties, in 1876. These spurs were merely intended to assist the current in scouring away the hard clay met with in various parts of the channel between the jetties, and were to be removed as soon as the channel had been sufficiently deepened. This concentration of the current was the more needed at the outer end of the channel on account of the leakage which occurred through the jetties all along, amounting at the extremity of the channel to a loss of from 35 to 40 per cent. of the whole volume entering the channel. The jetties could have been made more watertight at the commencement if a larger proportion of stone to willow than 1 to $5\frac{1}{3}$ had been easily procurable; the consolidation of the works will, however, gradually reduce the leakage.

The channel across the shoal at the head of the South Pass was improved, at the end of 1876, by contracting the funnel-shaped entrance to the South Pass into a uniform channel, 850 feet wide, by means of piers; and by sinking mattress sills, 2 feet thick, 70 feet wide, and 3000 feet long, across the entrances to the South-West Pass and the Pass à l'Outre, so as to close the entrances into these two larger Passes and increase the current entering the South Pass. A narrow channel was dredged through the shoal; and the floods in 1877 scoured out a good channel.

Effects of Jetties at Outlet of the South Pass. The results attained by these works have proved most satisfactory. Two years after their commencement the channel over the bar at the outlet had been increased from 8 feet to 20 feet in depth, and across the shoal at the entrance to the South Pass from 15 feet to 20 feet for a width of 400 feet, and 30 feet in the centre. At the middle of 1879 the channel over the bar had been deepened to 28 feet; and, with the exception of a length of 350 feet, there was a continuous channel between the jetties over 30 feet in depth. The depth over the shoal at the head of the Pass had reached 24½ feet.

According to the description given by Mr. Corthell in 1880[1], the improvement of the channel has continued since 1879. The 26 feet channel has widened out from 200 to 260 feet; the 30 feet channel has a minimum depth of 31 feet, and a minimum width of 60 feet, with a width of 360 feet just within the sea ends of the jetties (Plate 21, Fig. 2). At the head of the South Pass the 30 feet channel connects the deeper water of the main river with that of the Pass, and its minimum width is over 350 feet.

The increase in depth over the bar of the South Pass amounts to 23 feet, and over the shoal at its head to 15 feet; and these results have been accomplished within the short space of five years.

Whereas, previously to 1875, the South-West Pass afforded a channel, for the trade of the Mississippi into the Gulf of Mexico, of only 18 feet in depth, which could with difficulty be maintained by constant dredging, there is now an outlet channel provided, through the South Pass, more than 30 feet deep, which is maintained by the natural scour of the river.

Maintenance of the Outlet of the South Pass. It was anticipated, before the works were commenced, that the bar would be merely forced further seawards by the con-

[1] A History of the Jetties at the Mouth of the Mississippi river. E. L. Corthell. p. 222.

centrated current, and that it would form again beyond the ends of the jetties, and that consequently a periodical extension of the jetties would be necessary. Hitherto, however, the scouring action has been so powerful between the jetties, that it has extended its action beyond them, and has actually increased the depth in the Gulf in front of the outlet. The continuance of this very satisfactory condition will depend on the action of natural causes in the Gulf. Unless a sufficiently strong littoral current exists across the ends of the jetties to convey away the enormous quantity of material brought down by the river, deposit must be gradually accumulating in front of the outlet, forming the nucleus for a future bar. Owing, however, to the distance to which the sediment is transported by the powerful river current, and the depth attained before deposit can take place, it is probable that the accumulation would not be raised sufficiently to affect the outlet for some time to come. Mr. Corthell states that a strong littoral westerly current exists, produced by the prevailing winds; and that there are no signs of any accumulation of deposit in the Gulf in front of the jetties. If these views are correct, there is a good prospect of the easy maintenance of the outlet. The existence of the littoral current has, however, been questioned; and the effect of wind in producing a current does not generally extend to any considerable depth.

A longer period must elapse before any definite conclusion can be arrived at as to the accumulation of deposit; but it may be fairly said that the results attained, in so short a time, are amongst the most remarkable achievements of river engineering.

Lake River Outlets. Several of the rivers flowing into the large inland lakes of North America have had their outlets deepened by training their channels into the lake by means of crib-work piers, and by dredging between the piers. The outlets of the Chicago, Buffalo, and other rivers, have

been improved in this manner. The current, however, of the rivers has not apparently much power of maintaining a deep channel. Moreover, the littoral current, along the shores of the lakes, produces an advance of the shore against the outside of the pier on the side from which it flows; and finally, the accumulation of drift overlaps the pier, and forms a bar across the river. This is generally remedied by an extension of the windward pier, which, being composed of timber cribwork, filled with stone and sunk in position, is cheaply constructed. Recently, however, long breakwaters, similar in construction, but starting from the shore some distance apart, extending into deep water and then converging, and sheltering a large area in front of the river outlet, have been adopted[1]. Extensions of this kind are being carried out, on a large scale, for providing increased harbour accommodation, and sheltering the outlets of the Chicago and Buffalo rivers. Such extended works belong more to harbour construction than to the improvement of river mouths. They will, however, protect the mouths of these rivers from the inroad of sand, drifted along by waves and the littoral current; and perhaps, from the distance to which they extend from the shore, they may enable the advancing shore to attain a position of equilibrium before it reaches the harbour mouth.

Concluding Remarks. The improvement of tideless river mouths is a less complicated problem than the improvement of tidal rivers. Harrowing or stirring up the deposit on the bar is useless, as the river current, being unable to convey the matter it holds in suspension out to sea, cannot possibly carry off any additional material. Such a course could be of use only if the sediment was deposited when the river was low, and then advantage might be taken of the increased scouring power of the river in flood. The bar, however, in these rivers is mainly formed by the large amount of sediment brought down by a flood, at which period scraping on

[1] Report of the Chief of Engineers (United States) for the year 1879.

the bar would be useless; and the low-water discharge would have little transporting power.

Dredging can only prove a temporary expedient for deepening the outlet channel of a tideless river, as deposit is always accumulating for filling it up again.

The regulating and contracting of an outlet channel by jetties necessarily proves effective in deepening the channel, as the same discharge, or by stopping up other channels an increased discharge, is forced to flow through a channel reduced in width. The easy maintenance of the outlet of the channel, when formed, depends upon external causes beyond the control of an engineer; but an extension of the jetties is generally available for maintaining it.

The improvement of the outlets of the Danube and the Mississippi possess several points of resemblance.

In both cases, harrowing the bar was the first expedient tried, and resulted in failure. The contraction of the outlet channel by jetties, carried out across and beyond the bar, produced in both instances a remarkable deepening by the scour of the current. In neither case has an extension of the jetties been required since the works were completed, owing, in the case of the Danube, to the diversion of the suspended sediment by the southerly littoral current, and, in the case of the Mississippi, to the greatly intensified current by the stoppage of the other channels, the great depth into which the sediment-bearing current is carried, and possibly also to a littoral current. One of the minor outlets was selected in each instance for improvement, mainly on account of the smaller cost of the jetties; though the St. George channel at the Danube, and the South-West Pass at the Mississippi, would have been preferred by the engineers concerned in the works.

There is, however, one advantage in using a smaller outlet, provided that it is sufficiently large for navigation, namely, that the rate of progression of the delta in front is slower,

in consequence of the smaller amount of sediment brought down the smaller channel. This advantage, which has been fully realised at the Sulina mouth of the Danube, has been abandoned at the South Pass of the Mississippi, as the other outlets have been closed in order to provide an increased scour. Fortunately the natural conditions of the Gulf in front of the Mississippi outlet are favourable; otherwise the increased current might, as in the case of the Rhone, have compromised the maintenance of the outlet, owing to the increased burden of sediment which accompanies it.

Much has been accomplished, but much still remains to be done, for the improvement of rivers, and the development of inland navigation; and it is hoped that the results of experience, and the discussion of principles, contained in the foregoing pages, may aid in promoting that proper combination of theory and practice upon which all true progress in engineering science must be based.

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Improvement of Tideless River Mouths.

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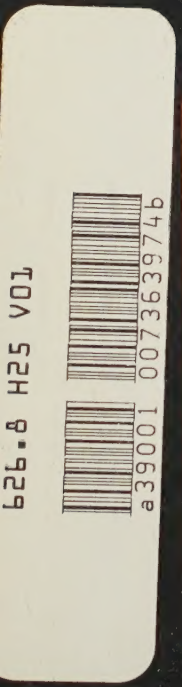

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